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Combining Lean and Six Sigma in the context of Systems Engineering design

TR Sreeram Asokan Thondiyath

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Combining Lean and Six Sigma in the context of Systems Engineering design

TR Sreeram and Asokan Thondiyath
Department of Engineering Design,
Indian Institute of Technology Madras, Chennai, India

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Abstract

Purpose – The purpose of this paper is to present a combined framework for system design using Six Sigma and Lean concepts. Systems Engineering has evolved independently and there are numerous tools and techniques available to address issues that may arise in the design of systems. In the context of systems design, the application of Six Sigma and Lean concepts results in a flexible and adaptable framework. A combined framework is presented here that allows better visualization of the system-level components and their interactions at parametric level, and it also illuminates gaps that make way for continuous improvement. The Deming's Plan-Do-Check-Act is the basis of this framework. Three case studies are presented to evaluate the application of this framework in the context of Systems Engineering design. The paper concludes with a summary of advantages of using a combined framework, its limitations and scope for future work.

Design/methodology/approach – Six Sigma, Lean and Systems Engineering approaches combined into a framework for collaborative product development.

Findings – The present framework is not rigid and does not attempt to force fit any tools or concepts. The framework is generic and allows flexibility through a plug and play type of implementation. This is important, as engineering change needs vary constantly to meet consumer demands. Therefore, it is important to engrain flexibility in the development of a foundational framework for design-encapsulating improvements and innovation. From a sustainability perspective, it is important to develop techniques that drive rationality in the decisions, especially during tradeoffs and conflicts.

Research limitations/implications – Scalability of the approach for large systems where complex interactions exist. Besides, the application of negotiation techniques for more than three persons poses a challenge from a mathematical context. Future research should address these in the context of systems design using Six Sigma and Lean techniques.

Practical implications – This paper provides a flexible framework for combining the three techniques based on Six Sigma, Lean and Systems Engineering.

Social implications – This paper will influence the construction of agent-based systems, particularly the ones using the Habermas's theory of social action as the basis for product development.

Originality/value – This paper has not been published in any other journal or conference.

Keywords Six Sigma, Lean, Continuous improvement, Quality, PDCA, Systems Engineering

Paper type Research paper

1. Introduction

Systems Engineering is an interdisciplinary approach that aims to achieve design solutions by combining systems, subsystems and components. Systems Engineering techniques are used in complex engineering scenarios including spacecraft design, computer chip design, robotic manipulators, software integration and engineering

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applications (Beude, 2009; Muller, 2013; McAdam *et al.*, 2012; Antony, 2014; Beesemyer, 2012; Yang *et al.*, 2007; Eng, 2011; Elm, 2005; Antony, 2010). Systems Engineering uses numerous tools to carry out modeling and simulation, analysis of requirements and scheduling to manage complexity of system integration and problem-solving (Medland, 1992). Through a series of well-defined steps, Systems Engineering defines the customer needs and progresses further toward design synthesis, realization, optimization and validation of systems. Traditionally, Systems Engineering has evolved independently, and there are numerous tools and techniques available to address issues that may arise in the design of systems. However, in the context of systems design, applying Six Sigma and Lean concepts leads to a powerful framework that allows an outside-in approach (Tremaine, 2009; Gibbons *et al.*, 2012). Such a framework allows better visualization of the system-level components and their interactions, and it also illuminates gaps and make way for continuous improvement. Tremaine (2009) and Fournier (2012) have independently assessed the subject of integration of Lean Six Sigma with Systems Engineering from a theoretical perspective. In literature, there have been limited attempts aimed at the integration of Lean Six Sigma with Systems Engineering (Fournier, 2012; Boehm *et al.*, 2012; Gibbons *et al.*, 2012; Hefner, 2010; Muller, 2013). Recent publications by Reosekar and Pohekar (2014), Cudney *et al.* (2013) and Drohomeretskiab *et al.* (2014) do not state any known references that directly address the integration of Six Sigma and Lean with Systems Engineering.

In the context of design, the importance of Systems Engineering cannot be overstated. Systems design allows hierarchical decomposition of design problems into smaller subsystems. The decomposition itself eliminates the inherent complexities and allows visibility of internal subsystems to lower levels and all the way to the parametric level. It is important for industries to remain competitive through innovation and continuous improvement. The scalability is the main challenge in systems approach. As the systems get more complex as in the case of space crafts and missile systems, the system-level interactions also increases exponentially resulting in several challenges including:

- large data exchange between subsystems;
- ability to respond/make decisions in time;
- identification of improvement opportunities such as design improvements or cost optimization; and
- interaction with legacy systems.

Some of these challenges in Systems Engineering could be addressed using Lean principles that focuses on waste reduction and Six Sigma to achieve reduction of process variation and lesser number of defects. The Lean and Six Sigma offers several other complementary benefits that could be used in the context of Systems Engineering. There are several success stories relating to the application of Six Sigma in large systems (Antony *et al.*, 2006; Ray and Das, 2009), for example, design of X-Ray systems by General Electric that adopted a Six Sigma approach combining Define-Measure-Analyze-Improve-Control (DMAIC) and Design for Six Sigma (DFSS) (General Electric, 2000). General Electric Medical Systems achieved the optimal design after a combination of iterative steps from 16 DFSS and 30 DMAIC projects. Similarly, in the context of Lean, application of Lean principles could be found in studies by

Antony (2014) and Cudney and Elrod (2011). Application of the Lean technique could help in reducing the number of iterations in systems design process, eventually leading to shorter lead time. The Systems Engineering is based on a reductionist philosophy, and given the complexities in the present-day data networks (e.g. Big Data, Cloud Computing, etc.) and product design scenarios (e.g. geographically distributed, reusable design objects, agent-based design, etc.), the systems approach should adapt to new and efficient ways (Prabhushankar *et al.*, 2009; Virani and Stolzar, 2014). Systems design could benefit if principles of Lean and Six Sigma are applied from the start of the design process. There is a need to weave the strands of Lean and Six Sigma with the fabric of traditional systems design engineering. This should result in a stronger platform backed by data and fact-based decisions where engineers could objectively evaluate their designs at a parametric level (supported by various design assessments). Related research work attempting to combine the systems approach with Lean and Six Sigma has highlighted a need for a more robust framework that brings the complementary benefits due to individual approaches (Tremaine, 2009; Fournier, 2012). However, no known attempts have explored the complementary aspects of combining Systems Engineering with Lean and Six Sigma in the context of parametric systems design. This paper presents a framework for systems design combining the complementary aspects of Lean, Six Sigma and Systems Engineering. The objective here is not to arrive at a rigid framework that would fit in all scenarios but to create a recipe consisting a complementary set of steps that brings the best of these approaches. The triumphs and tragedies with a rigid implementation is discussed in detail by Goh (2010). The ingredients of this framework would be based on the type of systems design problem at hand. The Deming's Plan-Do-Check-Act (PDCA) cycle is the basis of this framework. First, the Systems Engineering principles are summarized and then its alignment with Lean Six Sigma concepts are explored. The common framework is arrived at by mapping unique characteristics of Systems Engineering and Lean Six Sigma concepts. Three case studies are presented that emphasize the application of this framework in the context of engineering design. This is followed by an analysis of limitations and scope for future research.

2. Systems Engineering and Lean Six Sigma

In the context of engineering problem-solving, there are numerous approaches (structured and unstructured) that are outlined in the literature (Kusiak *et al.*, 1996). Of the several structured approaches, the ones based on Systems Engineering, Lean and Six Sigma (Figure 1) or combined Lean Six Sigma have evolved as the most widely used in product development (Antony, 2014; Tremaine, 2009; Bozdogan, 2010).

2.1 Systems Engineering

Similar to other structured approaches, Systems Engineering offers a multifaceted approach to parametric engineering design. With all the variants since its beginning in the 1940s, the ultimate goal in systems design approach is to satisfy customer needs throughout the design life cycle. This is a systematic thinking methodology and has found applications from simple to complex systems. For example, defense applications (e.g. design of missile systems), aerospace (e.g. design of aircrafts), software tools for design (e.g. I-DEAS, Pro-E, ABAQUS, etc.) and mechatronics (e.g. deployment of air bags in automobiles). The Systems Engineering approach uses both qualitative and

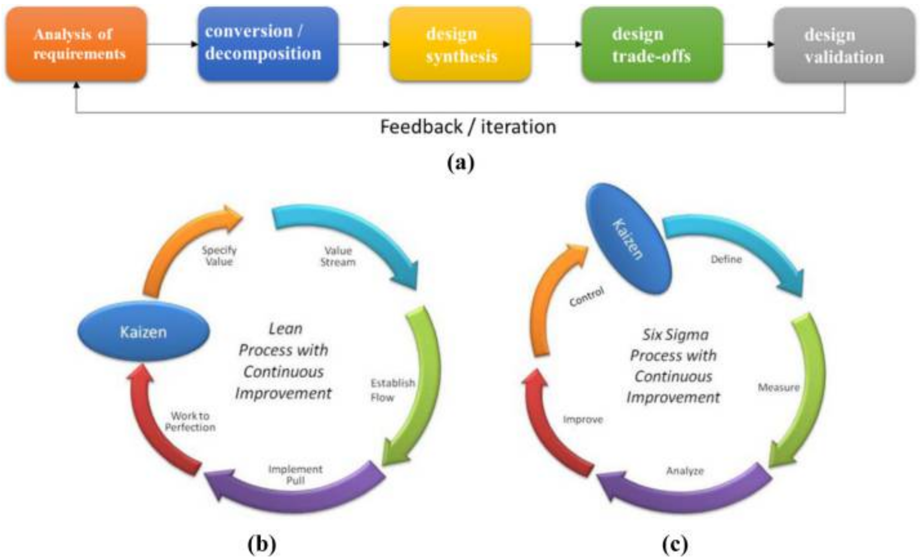


Figure 1.
(a) Systems Engineering; (b) Lean process; (c) Six Sigma cycle

quantitative techniques for problem-solving. In literature, some of the common steps include:

- analysis of requirements;
- conversion/decomposition of elements into design functions;
- design synthesis; and
- design tradeoffs, design optimization, testing, redesign followed by validation of the design (Beude, 2009; Boehm *et al.*, 2012).

Figure 1(c) shows a typical systems design scenario that is followed by most organizations. However, studies show that a critical evaluation of the Systems Engineering approach happened only in the past decade (Elm, 2005). The main points raised by Elm (2005) include the adaptability issues in the context of large problems. With a number of subsystems adding up to a large system, it is known that the complexity increases substantially with every addition of a subsystem component. Besides, at a parametric level and as depicted by Kusiak *et al.* (1996) in their graph-based approach, the effect due to the addition of subsystems tends to increase the design computation time in a non-linear manner. This increase is attributed to high network traffic at a system level. Given our present design challenges such as processing of high-volume data (e.g. multi-media content, design animations), autonomous design (e.g. selection of best design with respect to cost, strength and design agents) and design simulation (e.g. automotive crash test simulations), the original recipe of Systems Engineering may not be sustainable and hence calls for a hybrid approach.

2.2 Lean in product design

The concepts of Lean thinking has emerged from a philosophy that deployment of resources for any objective other than creation of value for the end customer as wasteful and aims to eliminate this waste (Enoch, 2013; Antony, 2014; Cudney *et al.*, 2013; Hoerl and Gardner, 2010; Hicks, 2007). From a practical implementation of Lean in engineering design, the Bosch Rexroth group outlines the Lean approach and practical challenges, but the implementation itself is not presented at a parametric level. As the design goes through several stages, a typical Lean implementation covers the five steps as shown in Figure 1(a). The Lean implementation emphasizes the smooth flow principle that helps identify quality problems present in the processes and enables elimination of wastes from the system. As process improvement is effected through the five steps in Figure 1(a), the wastes are eliminated in a consistent manner. This is, in principle, the same for a mechanical design process; however, at a parametric level, the application of Lean concepts is less explicit and is outlined here. It is not uncommon to see an optimal design shipped to a customer in a few weeks' time, where the actual value-added design time is only a few hours. Awareness of pockets containing non-value activities in a design process helps designers gain focus, prevent wastes and generate outputs in a more efficient manner. A preliminary design stage is shows in Figure 1. For example, as the figure shows, the parametric estimation network has several paths, and, from a Lean perspective, iterating through this entire network for design option is seen as a waste related to over processing. Therefore, a Lean design should operate on a reduced network. The reduction of such a network could be achieved either via the theory of confluences proposed by deKleer and Brown (1975) or by means of transfer functions as obtained by means of design of experiment or response surface methodologies. In effect, the reduced network, irrespective of the means to achieve the same, would be a much simpler representation essentially consisting of a start node and an end node, covering the parameters of interest. As the design process evolves, the teams typically suffer from multi-tasking, which if not managed well introduces defects (e.g. incorrect geometry creation or incorrect choice of parameters for a finite element model) in a design process. In addition, any internal or external sourcing of design task or information may also lead to waiting (e.g. material information, change in design requirements and dependencies at the supplier end) and even, in some cases, under-utilization of design skills (e.g. utilization of an external resource when skilled designers are available internally). Effective project planning, use of Computer Supported Cooperative Work tools would help overcome some of the wastes and improve the efficiency in a design process (Grasso and Convertino, 2012).

2.3 Six Sigma in product design

Six Sigma is a disciplined and structured approach that helps focus on developing and delivering defect-free products and services. Sigma is a statistical term that indicates how far a given product/process deviates from an ideal state. The central theme behind Six Sigma is to discover the root cause of the problem that is causing defects and a strategy is systematically figured out to remove these defects and get as close to "zero defects" as possible. To reach the Six Sigma level, a process must produce no more than 3.4 defects per million opportunities. The Six Sigma technique is about moving the mean to a desired level and reducing the variation to achieve desired quality levels. In the literature, the approaches are based on DMAIC [shown in Figure 1(b)] and DFSS. Typically, the former method is adopted for improving existing products/processes, whereas the latter is used for developing new products/processes (Pyzdek, 2003). In the context of engineering design, there are several attempts that talk about the structured

DMAIC/DFSS application to product design. The work by Sony and Naik (2012) shows that Six Sigma, although very successful in structuring the design stages, impacts the ability to innovate in a design process. Their work presents the application of conjoint and Taguchi techniques to assess design features using parametric studies. This is similar to the use of response surface techniques seen in feature-based designs (Thompson *et al.*, 2004; Santhakumar *et al.*, 2009). Other than the classical approaches of Six Sigma as witnessed in DMAIC or DFSS, there also have been recent applications of the same in a more hybrid manner to achieve superior results. An initiative by De Feo and Bar-El (2012) presents the I-DFSS approach, which is a combination of I-TRIZ and DFSS. This approach could be viewed as a step toward an autonomous Six Sigma-based prescriptive decision system. For example, under the umbrella of I-DFSS, there are early warning systems that evaluate the risk of a design. The same could be extended to create a fully prescriptive analytics model and come up with design alternates with associated SWOT analysis. The work by Natarajan *et al.* (2011a, 2011b) presents a yet another theoretical approach that combines elements of DMAIC, DFSS and TQM for NPI work. The research work thus far on NPI and Six Sigma raises a fundamental question on whether Six Sigma should adapt to the existing design process in an organization or the organization must be changed completely to adopt Six Sigma framework and starts operating on that basis. Ericsson and Lillieskold (2012) emphasize that a design process could adapt to include DMAIC/DFSS tools, as organizations often find it overwhelming to choose the right Six Sigma tool (Parast, 2011). This is a common issue experienced by most organizations and the solution to this may be seen in approaches such as Lean Six Sigma that is both flexible and adaptable to both transactional and manufacturing processes (Antony, 2014; Goh, 2010; Hasenkamp and Olme, 2008). From a systems design standpoint, we may readily observe that the organizations that are driven by old Systems Engineering habits would benefit by combining the Lean and Six Sigma approaches. This is not only in terms of the variety of tools that help in decision-making but also in streamlining the design process, resulting in waste- and defect-free scenarios. To this end, the individual approaches of Systems Engineering, Lean and Six Sigma are reviewed, covering key developments in engineering design in general and parametric design in particular. However, they offer several complementary benefits and are explored next.

3. Complementary aspects

There are several common aspects in these approaches, whether based on Lean or Six Sigma or Systems Engineering. It is important to realize their complementary nature in a common setting that effectively combines the individual approaches.

3.1 Common and unique features

Systems Engineering starts with the analysis of requirements, where all the design specifications, material definitions, etc. are obtained. The customer needs are identified reviewed and transformed into a set of objective definitions that capture what the system is expected to do. The requirements are elicited and documented and a baseline is created at this stage. This is similar to the DMAIC recipe, where the Voice of the Customer (VoC) is captured and converted to Critical Customer Requirements. Similarly from the business side, the requirements are also captured. Lean approaches this step from the creation of value to the customer by eliminating wastes from the design process:

- *Conversion/decomposition*: This is a stage where the system is expanded to its nth level, similar to a tree diagram. For example, in the case of a valve design, the enclosure and spring could be seen as subsystems. The network of parameters would represent the design knowledge at the subsystem level, which is subject to design constraints and rules before a solution is obtained. This treatment is unique in Systems Engineering, whereas, in Lean or Six Sigma, this is usually at a design process level. The decomposition is a unique step in Systems Engineering, however, the equivalent of which could be seen as a process map in DMAIC and value stream map in the case of Lean. A value stream focuses on flow of design information (or goods in manufacturing or shop floor) in a design process with special reference to cycle times, defects, wait times, design skill usage, etc. Process mapping captures inputs and outputs of every step in a design process. In addition, a process map may also hold information related to criticality of the step such as controllability of steps or availability of standard operating procedures.
- *Design synthesis*: This includes formulation of a design solution that satisfies the design requirements. This is consistent with the Improve phase of the DMAIC methodology, where often tools such as a Pugh matrix are used to arrive at the best choice for design. In Lean methodology, this step is visualized as a free-flowing process after removing all the functional barriers and achieving an error-free design solution.
- *Design tradeoffs*: In a systems design problem, a synthesized solution could potentially be in a conflicting scenario, given numerous subsystems and parametric interactions. To achieve tradeoffs in design, Systems Engineering offers techniques based on constraint relaxation or Game Theory. Although DFSS-based approach in Six Sigma captures tradeoffs using tools such as quality function deployment (QFD), an explicit treatment is not given in the traditional Six Sigma recipe. This qualitatively agrees with the removal of barriers or bottlenecks in a Lean context; however, design tradeoffs are treated in detail in systems design approach.
- *Design validation*: This is a standard end check point, where the systems and DMAIC/DFSS approaches are similar. The main activities within this step include finalizing the design, design testing, preparation of final documents and establishing design controls, etc. In Lean design, customer pulling the value with final checks and balances on designed product and standardization using tools such as 5S is generally observed.

3.2 Complementary features

The systems design approach allows decomposition at the parametric level. This is accomplished using techniques based on the graph theory. The lean principle allows the reduction or simplification of a design network of parameters, allowing a simpler representation. Besides, the Lean approach offers ways to minimize the wastes and redundant steps in the process. The reduction of wastes may be seen as either elimination or simplification of steps in the design process. The design tradeoff techniques using Game Theory and constraint relaxation are given importance in systems design and this could be used in association with DFSS tools such as QFD. There are several benefits that result from the combination of the approaches presented in Figure 2 and are captured in a framework presented next.

4. Combined framework

A framework combining three techniques based on Six Sigma, Lean and Systems Engineering is presented in Figure 3. Each technique has evolved independently given the fact that the origin of Six Sigma and Lean may be traced back to Systems Engineering. It is not the objective of this paper to prescribe a recipe for all engineering systems design. However, it is important to bring together the approaches under a common framework. The optimal combination of these approaches could be determined based on the problem. With the generic PDCA forming the basis of this framework, a combination of steps is shown in Table I and could be further expanded, if needed. The standard PDCA cycle by Deming (also referred to as Shewhart Cycle) is a methodology that was aimed at iterative problem-solving. The technique, since its origin, has been applied to a range of engineering design problems (Deming, 1986; Sokovic *et al.*, 2010; Jou *et al.*, 2010). Even in the classic Six Sigma philosophy (based on DMAIC) adopted by several leading organizations including General Electric, PDCA is seen as the basis, although several variants have been discussed in the literature (Anderson, 2011). Several of these implementations have suffered from severe sustainability issues due to

Figure 2. Common characteristics of Lean/Systems Engineering/Six Sigma

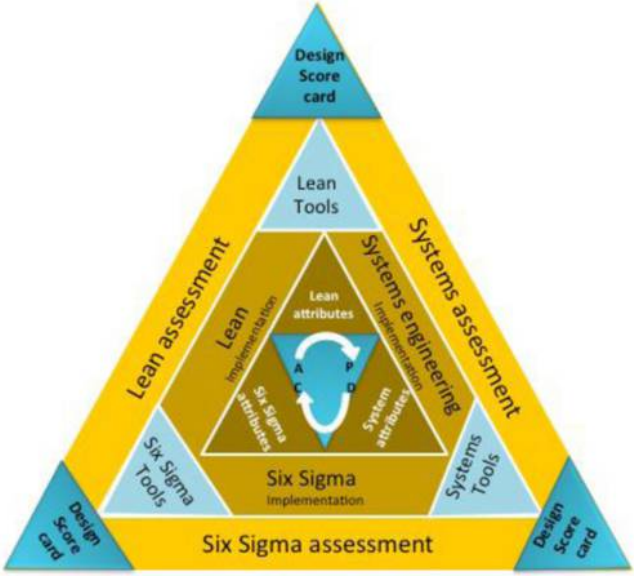


Figure 3.
The design framework

lack of pre-implementation studies (or the post-implementation assessment) that effectively determine an organization's culture (Bozdogan, 2010). Although some reviewers have been critical on the adoption of PDCA as the basis for improvements, the authors view it as a generic framework that could be easily adapted for systems design. This view is opposed to force fit the traditional DMAIC- or Systems Engineering-based tools and concepts without carefully considering the requirements of the design.

4.1 PDCA as the basis

The framework presented in Figure 3 captures the steps generally adopted in Lean, Six Sigma and Systems Engineering and these steps combined using the PDCA approach. In general, implementation of any process/product improvement should be able to clearly define the independence between processes and people so that the improvements are indeed sustained on a longer-term basis. The power of the PDCA approach lies in its flexibility and simplicity and hence any concept/tool from the existing Lean, Systems Engineering or Six Sigma approaches could readily be integrated to this framework. Besides, this PDCA framework explicitly supports flexible, continuous improvement. In the PDCA recipe, the *Plan* phase is where the problem is defined. This is the stage where the baseline supporting the business case is explicitly identified and the team embarks on a journey to capture the design requirements, map the design process, identify the redundant steps in the process and root causes of the problem. The *Do* phase typically involves the solution schemes or synthesis of the design. This may also require adopting a tradeoff solution based on some rational negotiation strategies (Nash, 1950). Once a solution is adopted, the same is tested to ensure that the output of the solution satisfies the requirements and constraints. The next stage is the *Check* phase and the primary aim here to ensure that the obtained solution is indeed stable and predictable. Besides, implementations could start in the *Check* phase and could go well in to the *Act* phase. *Act*

Table I. Steps in the combined framework

Process/product improvement methodologies and systems design-key steps								
Six Sigma		Lean			Combined framework*			
DMAIC (Improvement opportunity)	DFSS (To identify a new product or service)	DMAIC	DFSS	Systems Engineering	Plan	Do	Check	Act
Voice of the customer	Voice of Customer/ requirements collection	Current state assessment	Define the Design KPIs	Collection of user requirements	VoC (analysis of requirements)	Concepts-design synthesis	Testing/ validation	Sustaining/ 5S
Data analysis–measurement of the as-is state	Data analysis	Future state map (VSM after Kaizen aimed at reducing wastes)	Create lean design process	Functional analysis	Process mapping/ design decomposition	Design tradeoff – optimization	Further Optimization	Future improvements
Root cause analysis	Conceptual designs-synthesis and selection of design elements	Identify process improvement opportunities (prioritization)	Design decompositions	System specifications/ architecture	Wastes/ redundancy checks	Negotiated solution	Implementation	Design process documentation
Generate solutions	Generate and evaluate possible designs, design risks, product management	Kaizen – implement change(s) and monitor	Design reviews	Design analysis/ tradeoff/ optimization	Baseline design	Simplified design process	Design reviews	Design reviews
Implement solutions	Design control	Audit and sustain	Design checklist/design scorecards	Design implementation	Root cause analysis	Design documentation		
Control/change plan	Documentation	Continuous improvement	Design manuals/controls	Verification/ validation	Design reviews	Design reviews		

Note: * This represents a possible combination of steps from Six Sigma, Lean and Systems Engineering approaches into a combined framework consists of product/process control measures. The *Act* stage concludes by identifying the next steps for further improvement after a period of sustaining results conforming to specifications, setting the stage for next level of improvement and follow-up Kaizen events.

4.2 Phases in the framework

To consolidate and anchor the references of steps in the design framework, it is divided into four phases – plan, do, check and act. In the present framework, we have combined the common steps of Systems Engineering, Lean and Six Sigma methodologies as identified in Section 3. The key steps are enlisted in Table I and this could, however, be extended to add more steps, if required. The table also shows the corresponding tools that are mapped to a given step within each phase. For example, in a design scenario, involving multiple solutions, a tradeoff study based on Game Theory or constraint relaxation is deployed to arrive at a single solution (Sreeram, 2000). Table I covers the complementary capabilities of Lean/Systems Engineering and Six Sigma.

5. Case studies

As a means to evaluate the framework, three case studies are considered here:

1. design of a pressure vessel;
2. design of a relief valve; and
3. design and manufacturing of an Autonomous Underwater Vehicle (AUV).

5.1 Design of a pressure vessel

A design example of a pressure vessel is considered here as a case to demonstrate the use of the PDCA framework. Table II highlights the steps followed and the key technical aspects within these steps. The highlight in this case study is to emphasize the need for rational protocols for design tradeoff during product development process, which is followed in traditional systems design. Based on the Lean principles, the network is in a simplified state due to the simple nature of the design itself. There are no multiple paths or redundancies in the design network. Depending on the complexities present in a network, the same could be reduced to eliminate over-processing during the iterative design. The process of reducing design networks is based on the theory of qualitative and quantitative influences (Kusiak *et al.*, 1996; Sreeram, 2000). Traditional Six Sigma procedures do not explicitly present techniques for tradeoff or negotiation. In this context, the designers have individual preferences on a specific design attribute, for example, the attributes could be weight or cost. Figure 4 shows a symmetric pressure vessel with hemispherical ends that is to be designed by two designers. The design requirement is the vessel should withstand a pressure of $p = 800$ KPa. The inner radius of the vessel (r) is given as 1.8 m and length (l) is 10 m. The constraints are: wall thickness $t < = 0.2\,m$, outer radius $x < = 0.2\,m$ and $\sigma_{\text{hoop}} < = \sigma_{allow}$. The goal here is to achieve a design satisfying the design constraints,. As the design progresses through the steps in PDCA framework, the design problem is specified as a parametric graph to enable dependency-based qualitative and quantitative reasoning. The graphs in Figure 4 are already in the reduced form that would provide the designers necessary qualitative as well as quantitative data on the design constraints. As such, there are no redundancies in the process map. From a Lean design philosophy, the reduced design graph would represent effective dependencies between two or more design parameters. This implies

Table II. Application of framework to the pressure vessel case study

Plan	Do	Check	Act
Combined systems-Six Sigma-Lean framework-PDCA			
🟩 VoC (analysis of requirements)	🟩 Concepts-design synthesis	🟩 Testing/validation	Sustaining/5S
🟩 Process mapping/design decomposition	🟩 Design tradeoff-optimization	Further Optimization	🟩 Future improvements
🟩 Wastes/redundancy checks	🟩 Negotiated solution	🟩 Implementation	🟩 Design process documentation
🟩 Baseline design	Simplified design process	🟩 Design reviews	🟩 Design reviews
Root cause analysis	🟩 Design documentation	Items marked green were the steps carried out in this case study	
🟩 Design reviews	🟩 Design reviews		
Combined systems-Six Sigma-Lean framework-pressure vessel case study			
The voice of customer/requirement: the pressure vessel design should be safe	Design concepts generated by conflicting designers	For a wall thickness of 0.125 m, the design meets customer requirements	No specific 5S implementation was carried out
A design decomposition of parameters was accomplished using graph theory	Utility functions generated based on design requirements	Further Optimization not carried out	Future improvement suggested by the design team included use of alternate materials, DoE-based study using Hyperstudy and Abaqus FEA software
No redundancy; no design wastes due to multiple paths representing over processing or inventory	Negotiated solutions of Nash and Kalai-Somordinsky evaluated	Finalized design of the pressure vessel adopted	Design process was documented including the suggested improvements
Baseline design of the pressure vessel was completed	No further simplification of design network carried out	The design was documented and reviewed with stakeholders	Final design review completed including sign off documentation
No specific root cause analysis was carried out	The design process, parameters, conflicting scenarios, all documented		
Design review completed and possible design conflicts identified	Design reviews indicated a possible material replacement		

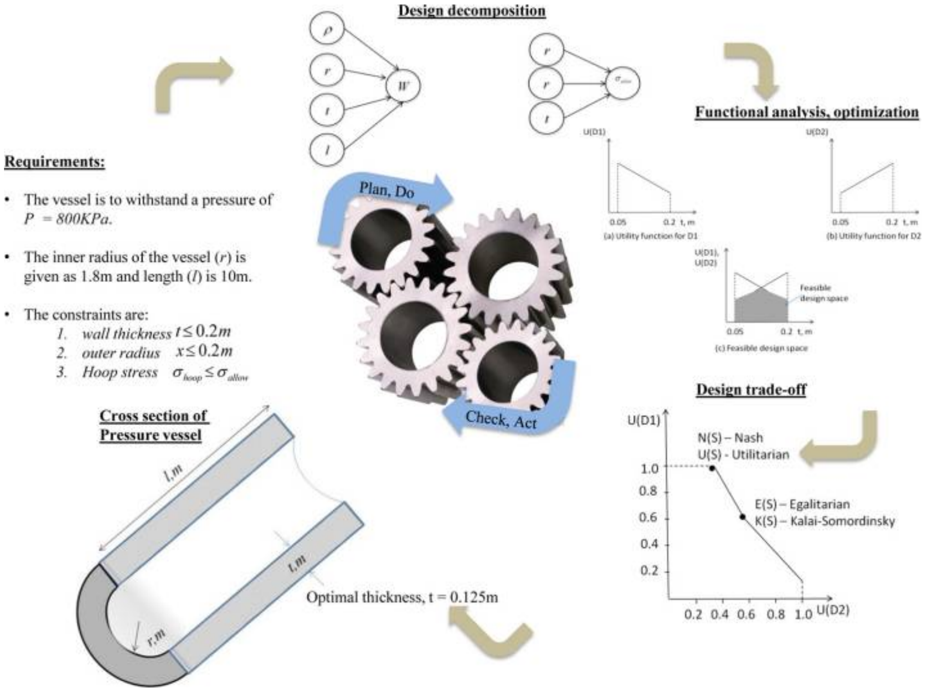


Figure 4.
Case study for pressure vessel design

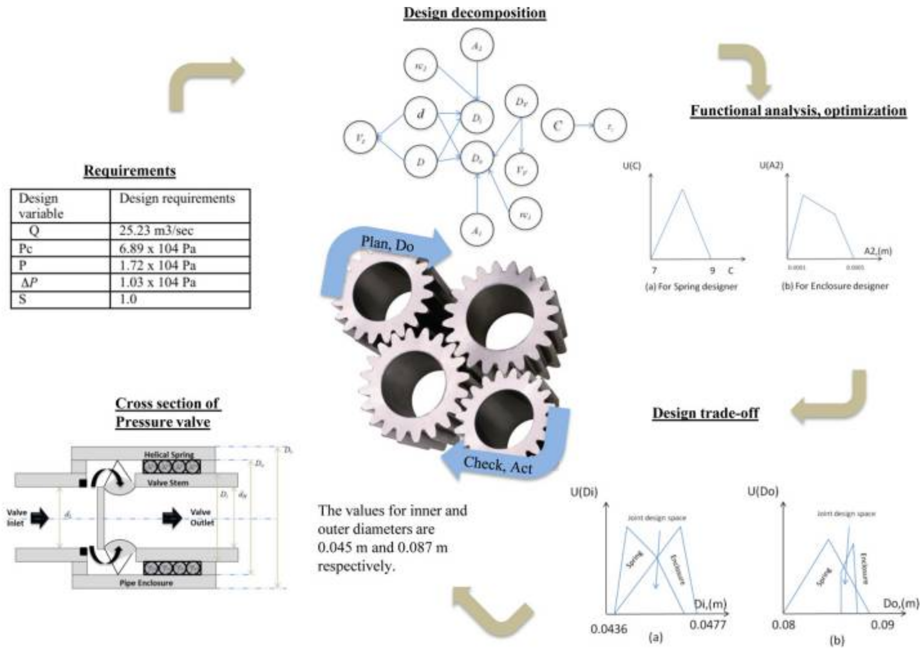
that there may be paths in the original design graph that may be considered as “waste”. As two designers (referred to as D1 and D2) collaborate to arrive at an acceptable design, D1 prefers to minimize the weight of the vessel (W), whereas D2’s goal is to minimize the hoop stress (σ_{hoop}). The design utility functions for these two parameters [W and σ_{hoop}] as a function of thickness “t” are shown in Figure 4, evidently leading to a conflicting scenario. To resolve the conflict and reach a negotiated settlement between designers, a set of game theoretic solutions is obtained. As a first step, a joint utility curve is plotted under normalized coordinates as shown in Figure 4. The Nash [N(S)] and Utilitarian solutions [U(S)] resulted in maximum benefit for designer D1 and the outcome corresponds to a value of 0.05 m for wall thickness. The Kalai-Somordinsky and Egalitarian solutions K(S) and E(S) resulted in a value of 0.125 m for the wall thickness. In the given scenario, the Kalai-Somordinsky solution is taken as the final solution and the negotiated value for the wall thickness is 0.125 m (Figure 4).

The design stage where the standardization of final outcome and identification of further opportunities to improve the design is termed as the act phase. Typical steps include type of material for vessel, manufacturing process, cost and type of application. The design graph in Figure 4 is still applicable for all such future optimization requirements (assuming the parameters are directly proportional). From the perspective of design control, the value of pressure is monitored to ensure safety of a given vessel. Analysis of this case study in terms of the proposed frame work is presented in Table II. A more complex scenario involving several design parameters is discussed next.

5.2 Design of a relief valve

In engineering applications, valves are commonly used to regulate the flow and to relieve excessive pressures in closed enclosures (Lyons, 1982). Figure 5 shows a poppet relief valve consisting of three components: a helical spring, a valve stem and a pipe enclosure. The helical spring and valve stem are both enclosed in a pipe. The fluid is allowed to flow through the valve from inlet to outlet as indicated by the arrows in figure. The fundamental principle here is that the flow occurs only when the pressure of fluid exceeds the cracking pressure of the valve. The flow of the fluid is cut off for fluid pressures below the cracking pressure as the helical spring presses the seal against the valve inlet preventing further flow. In this study, the design of poppet relief valve is viewed as a PDCA process from the valve, spring and enclosure perspectives. Table I refers to a generic design process; however, in the context of this case study, only relevant steps are demonstrated in Table III, highlighting the process mapping, reduced process map and design trade-off.

As the design process evolves starting from the *Plan* phase, requirements for the design are established. The spring and enclosure designers evaluated the unknown variables and formed the initial design (Kusiak*et al.*, 1996). A comparison of common variables indicated the presence of conflicts between spring and enclosure designers on the values of internal and external diameters as 0.0442 and 0.0876 m and 0.0652 and 0.0896 m, respectively. Thus, a conflict was detected between the two designers on the values of D_i and D_o. The first step in conflict resolution was the dependency-based reasoning on a network of design constraints as shown in Figure 5. The designers determined the qualitative and quantitative dependencies (deKleer and Brown, 1975; Sreeram, 2000). The negotiation between conflicting designers was carried out based on



Design variable	Design requirements
Q	25.23 m3/sec
Pc	6.89 x 104 Pa
P	1.72 x 104 Pa
ΔP	1.03 x 104 Pa
S	1.0

The values for inner and outer diameters are 0.045 m and 0.087 m respectively.

Figure 5.
Case study for pressure relief valve

Table III. Application of framework to the valve design case study

Plan	Do	Check	Act
Combined systems-Six Sigma-Lean framework-PDCA			
VoC (analysis of requirements)	Concepts-design synthesis	Testing/validation	Sustaining/5S
Process mapping/design decomposition	Design tradeoff-optimization	Further Optimization	Future improvements
Wastes/redundancy checks	Negotiated solution	Implementation	Design process documentation
Baseline design	Simplified design process	Design reviews	Design reviews
Root cause analysis	Design documentation	Items marked green were the steps carried out in this case study	
Design reviews	Design reviews		
Combined systems-Six Sigma-Lean framework-valve design case study			
The voice of customer/requirement here is the valve should be operational according safety standards	Design concepts generated by conflicting designers-enclosure and spring	The values of internal and external diameters were evaluated	No specific 5S implementation was carried out
A design decomposition of enclosure and spring design is accomplished using graph theory	Utility functions generated based on design constraints for spring and enclosure perspectives	Further Optimization not carried out	No specific improvements were suggested
No redundancy; due to presence of several parameters with multiple paths indicated over processing	Negotiated solutions of Nash and Kalai-Somordinsky evaluated	Finalized design of the valve adopted	Design process was documented including the suggested improvements
Baseline design of the value from enclosure and spring perspectives completed. A QFD tool was used	Reduced network evaluated eliminating redundant and multiple paths (over processing)	The design was documented and reviewed wit h stakeholders	Final design review completed including sign off documentation
No specific root cause analysis carried out	The design process, parameters, conflicting scenarios, all documented		
Design review completed and possible design conflicts identified between enclosure and spring designs	Design reviews were conducted		

the Game Theory approach – Nash, Kalai-Somordinsky game solutions. The utility functions for controlling decision variables were formed with respect to each conflicting perspective (Figure 5). For the spring designer, the spring index (C) was chosen as the controlling decision variable. This choice was based on the constraint on the installed length of the spring *Li*. For the enclosure designer, the corrosion resistance allowance A_2 was selected as the controlling decision variable. This was the only design variable that could be relaxed to generate utility for D_i without violating the design specification. The utility functions specified by the designers for the respective controlling variables are shown in Figure 5. The profile for C in Figure 5 is based on the limiting constraints. The utilities for the conflicting variables D_i and D_o were evaluated by the designers and are shown in the figure. When the feasible design region was formed (between the designers and not shown here), it was found that, for D_o, there was some common design space, suggesting the possibility of an agreement between the designers. However, for D_i, there was no such common design space requiring a redefinition of the utility functions. The spring designer relaxed the constraint on spring index (C) to a wider range. The re-evaluated utility functions showed the existence of a feasible design space between the designer utilities (figure). The negotiated solution (Kalai-Somordinsky) was evaluated to be 0.0446 and 0.0871 m, respectively, for the inner and outer diameters. The valve case study presented here is an extension of Section 5.1 in a more complex setting, especially the part on parametric design decomposition.

More design parameters are involved resulting in a more complex set of design interactions and objectives. The first two case studies focused on two key aspects of the combined framework:

(1) design decomposition and reduction of design networks; and

(2) design tradeoffs.

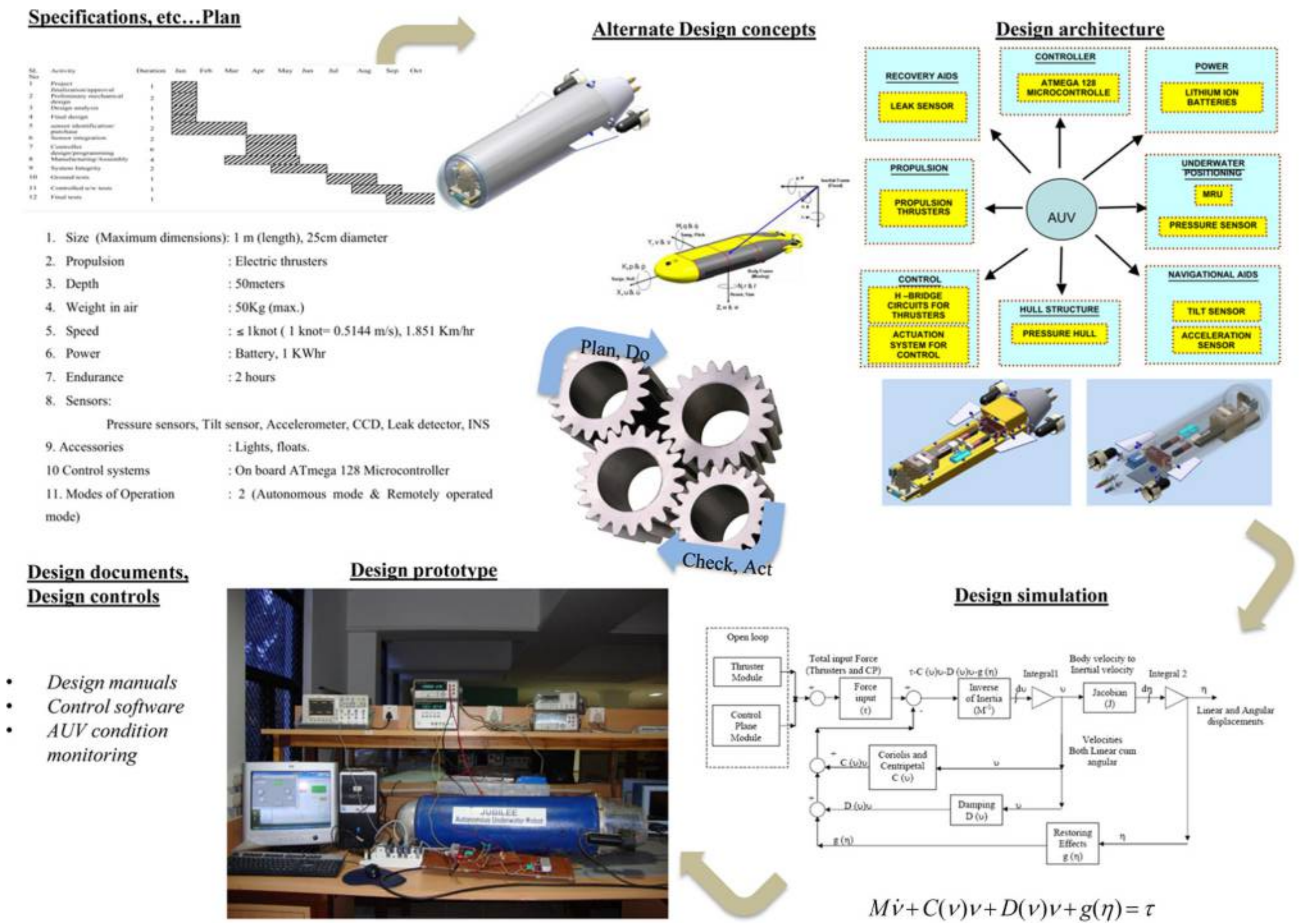
The analysis of this case study in terms of the proposed frame work is presented in Section 6. A more elaborate case study is considered next that covers the full cycle of a typical product development scenario.

5.3 Design of an AUV

The objective of this case study was to develop a predictive model for systems design of an AUV-type vehicle as well as developing suitable control strategies and algorithms for various types of operations. The development of AUV was accomplished by a geographically dispersed team including designers (mechanical, software and controls), manufacturing experts, testing and validation engineers. The objective was to arrive at an AUV prototype, given the design specifications. Based on the combined framework, the system-level design problem was analyzed to identify the architectural elements of the AUV. The overall PDCA cycle (Table IV) for the AUV design is shown in Figure 6. Starting from the concept design, several design options were considered and the flat fish-based AUV design was selected based on a Pugh selection matrix. The selection was narrowed down based on the requirements on higher payload and better stability. Further optimization was carried out using Taguchi's robust design concepts (Santhakumar *et al.*, 2009). Based on the design performance, the AUV design was finalized and verified through experimentation. Two important constraints considered in the *Do* phase were the *buoyancy of the vehicle* and *control energy* needed for the vehicle to stabilize. As per the VoC, the vehicle needs to have positive buoyancy so that, in the

Table IV. Application of framework to the AVU design and manufacturing case study

Plan	Do	Check	Act
Combined systems-Six Sigma-Lean framework-PDCA			
VoC (analysis of requirements)	Concepts-design synthesis	Testing/validation	Sustaining/5S
Process mapping/design decomposition	Design tradeoff-optimization	Further Optimization	Future improvements
Wastes/redundancy checks	Negotiated solution	Implementation	Design process documentation
Baseline design	Simplified design process	Design reviews	Design reviews
Root cause analysis	Design documentation	Items marked green were the steps carried out in this case study	
Design reviews	Design reviews		
Combined systems-Six Sigma-Lean framework-AUV design and manufacturing case study			
The voice of customer/requirement here is to develop a stable AUV	Design concepts generated by conflicting using Pugh matrix were proposed; DFMA tool used to assess manufacturability	The design prototype was built and tested under controlled conditions	5S implementation was carried out to maintain the testing lab area; optimized model of AUV tested
A design decomposition AVU system was accomplished	For conflicting entities, a constraint relaxation based on graph theory was utilized	Further Optimization not carried out using Taguchi's robust design technique	Improvements were suggested using a change integration fish bone
There were several interacting sub systems and presence of multiple paths indicated over processing	The constraint-based approach used the theory of qualitative and quantitative influences to arrive at an acceptable design	Matlab-based model was used to study the simulations; Optimized design of the AUV adopted	Design process was documented including the suggested improvements
Baseline design completed. A QFD tool was used A design FMEA was also carried out to identify the possible failure modes	Reduced network evaluated and eliminated redundant and multiple paths (over processing)	The design was documented and reviewed with stakeholders	Final design review completed including sign off documentation
Root cause analysis was performed at various sub system levels (propulsion, power unit and hull structure, etc.) also focusing on the possible failure modes	The design process, parameters, conflicting scenarios, all documented		
Design reviewed with sponsor and possible design conflicts identified between hull structure and navigational systems	Design reviews were conducted		



Sl. No	Activity	Duration	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1	Project finalization/approval	1										
2	Preliminary mechanical design	2										
3	Design analysis	1										
4	Final design	1										
5	sensor identification/ purchase	2										
6	Sensor integration	2										
7	Controller design/programming	6										
8	Manufacturing/Assembly	4										
9	System Integrity	2										
10	Ground tests	1										
11	Controlled u/w tests	1										
12	Final tests	1										

1. Size (Maximum dimensions): 1 m (length), 25cm diameter
2. Propulsion : Electric thrusters
3. Depth : 50meters
4. Weight in air : 50Kg (max.)
5. Speed : ≤ 1knot (1 knot= 0.5144 m/s), 1.851 Km/hr
6. Power : Battery, 1 KWhr
7. Endurance : 2 hours
8. Sensors:

Pressure sensors, Tilt sensor, Accelerometer, CCD, Leak detector, INS

9. Accessories : Lights, floats.
10 Control systems : On board ATmega 128 Microcontroller
11. Modes of Operation : 2 (Autonomous mode & Remotely operated mode)

- *Design manuals*
- *Control software*
- *AUV condition monitoring*

$$M\dot{v}+C(v)v+D(v)v+g(\eta)=\tau$$

Figure 6.
Case study: design of an underwater robot

event of a system failure, the vehicle will come up. However, for the minimal control energy requirement of the designer, a neutrally buoyant system was the best design option. A tradeoff analysis was carried out during the *Check* phase and the best value for buoyancy was evaluated. Controller tuning was carried out using Taguchi's method and design optimization was achieved. Further to the development of the prototype, the design documents were developed and control measures were established in the *Act* phase.

6. Analysis of the framework

The framework presented here showed a way the three methodologies could be combined that offers advantages over the conventional approaches. Some of its benefits and the challenges in the light of practical implementation of the same are discussed in the following sections.

6.1 Benefits

The combination of Lean, Six Sigma and systems concepts provides a powerful mix for structured problem solving. Compared to several off-the-shelf implementations across industries, the platform based on PDCA offers distinct advantages. First this allows flexibility in bringing the necessary ingredients together; for example, early on during process mapping, removal of redundancies from a process results in a more efficient process. The present framework is not rigid and does not attempt to force fit any tools or concepts. The framework is generic and allows flexibility through a plug and play type of implementation. This is important as engineering change needs vary constantly to meet consumer demands. Therefore, it is important to engrain flexibility in the development of a foundational framework for design encapsulating improvements and innovation. From a sustainability perspective, it is important to develop techniques that drive rationality in the decisions, especially during tradeoffs and conflicts.

6.2 Integrated systems design framework and its components

Systems Engineering processes generally follow a procedural approach that governs the stage-wise design of complex products. Inherently, in the classical approach of systems design, the aspects on predictable mechanizations, reducing variation in a process or eliminating waste from a process have not been specifically dealt with. In so doing, the PDCA approach of systems design becomes well integrated and there are checks and balances in the overall structure that makes the approach more robust.

This allows less variation, for example, human cognitive process – as seen during a typical negotiation scenario. A new product development process would involve the QFD approach – the design functions captured by means of a house of quality will lead to situations that are conflicting in nature (Salah *et al.*, 2009). The overall design process is made more rational (by means of utility functions) and more objective by means of the game theoretic concepts. Yet, the negotiation process is distinctly different from what is generally observed during conflict negotiation outside the engineering context. The integration of Lean and Six Sigma principles makes the approach more holistic and inter-disciplinary in flavor. On a more finely granular level, the Six Sigma approach allows statistical inference of the relationships between the inputs and outputs. For example, in the valve design scenario, the performance variable is flow, Q. To achieve a specific level of performance, it is important to see how the variables interact at a parametric level. These relationships are explicitly brought out in terms of the constraint equations (constraint networks) in the approach leading to further segmentation and stratification of data. The application of Lean in the context of valve design is that, in the constraint network, only the reduced qualitative and quantitative dependencies are retained. Therefore, a designer looking for an estimate of a performance variable will readily have the quantitative dependencies of the variables under consideration, assuming a linear relationship between variables. However, in more complex scenarios involving non-linearity such as in the development of AUV (Section 5.3), the approach based on response surface methodology or transfer functions could be integrated to accomplish the predictive models.

In the PDCA-based framework presented in this paper, the assessment of these approaches is important and should be highlighted. Typically, the system-level scorecards are a good reflection of the same and this covers the overall key product performance variables. In addition to the product-level assessment, the approach-level assessment is also needed, and this would typically involve (but not limited to) surveys, measuring process capability, sustainability and internal design audits. The purpose of assessment in the context of this framework is not overstated; however, this paper has provided an overview of the same, whereas the subject on assessment merits a full paper.

6.3 Limitations

The PDCA-based framework presented here shows a way of combining Lean, Six Sigma and Systems Engineering concepts. Industrial problems are complex, and it is difficult to prescribe generic solutions for all design scenarios. For example, the initial design should reveal the nature of combination required as opposed to adopting a general design framework based on any of these concepts. Typically, this framework captures an instance of a combination, while acknowledging that several variations of the same could exist. The examples presented here demonstrate the applicability of the concepts covered in a common framework; however, real-world problems present a far more complex scenario.

7. Conclusions and future work

Systems Engineering techniques are used in complex engineering scenarios including spacecraft design, computer chip design, robotic manipulators, software integration and civil engineering applications. Systems Engineering uses numerous tools to carry out modeling and simulation, analysis of requirements and scheduling to manage complexity of system integration and problem-solving. In this paper, we have presented a generic framework combining Six Sigma, Lean system and Systems Engineering concepts for the design of complex systems. By combining these concepts, it has been shown that the design process becomes much more flexible and adaptable for a range of design scenarios. Systems Engineering is an interdisciplinary approach that aims to achieve solutions by combining systems, subsystems and components. Through a series of well-defined steps, Systems Engineering defines the customer needs and progresses further toward design synthesis, realization, optimization and validation of systems. Traditionally, Systems Engineering has evolved independently, and there are numerous tools and techniques available to address systems design issues. However, in the context of systems design, the application of Six Sigma or Lean concepts and tools leads to a complementary framework that allows outside–in approach as seen through the case studies presented here. This framework is useful and allows better visualization of system components, their interactions and helps identify gaps. Future research is expected to focus on more robust integration of Six Sigma, Lean and Systems Engineering techniques.

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Corresponding author

TR Sreeram can be contacted at: tr.sreeram@gmail.com