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Lean Systems Engineering (LSE): Hands-on Experiences in Applying LSE to a Student Eco-Car Build Project

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Abstract

The Systems Engineering (SE) field is moving rapidly into commercial industries. Also, SE has more recently been combined with *Lean* to make it more suitable for highly competitive applications. This paper seeks to explore the application of LSE in a practical project, including the design, build and test of an ultra energy-efficient vehicle for Shell Eco-marathon—an annual world-wide student competition. The objective is to identify critical factors for implementation of LSE essentials to teams managing the development of complex products. The environment is suitable for studying LSE implementation in a controlled manner, without many of the disturbing factors in industrial projects. The cyclic nature of the project—with new teams every year working to improve last year's systems—simulates common real-world problems such as lack of value due to information lost in handoffs and deficient documentation of knowledge. A lean assessment was applied to identify fields with the greater improvement potential: knowledge management and continuous improvement. It is concluded that *Visual Workflow Management* provides concurrent focus in both fields, while introducing lean to manage project work. Hence, the team achieved a culture for learning, communication and making knowledge transferable; changing the team culture was essential to make LSE successful.

Keywords: Lean concept; implementation; knowledge; visual workflow management; model-based SE, problem-solving.

1. Introduction

The competitive pressure on companies is steadily increasing as a result of the current widespread economic downturn, among other factors. To survive in today's hostile and dynamic business environment, companies must develop and deliver more desirable products ahead of their competitors—before new technology emerges or market conditions change. Value creation drives successful innovation, and with this comes the need for development of more complex products whose value proposition is linked to the integration of components and subsystems into a complete system, rather than to the set of individual components. In this perspective, Systems Engineering (SE) has become an increasingly popular approach in commercial industries, [1].

The lean concept has revolutionized the manufacturing industry in terms of productivity, cost and quality improvements over the past three decades. Lean has gone through the stages of being a true competitive frontier in

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its early days to becoming a benchmark for competitive manufacturing throughout the world in the'90s to shifting into a commodity in today's hypercompetitive business world. As a result, several companies are nowadays looking into new applications of the lean concept beyond the manufacturing environment, such as new product development (NPD), in order to sustain competitiveness. However, the application of the lean concept in NPD is not straightforward, and there are very few examples outside Toyota where companies have been successful in implementing lean practices in NPD [2]. The reason(s) could have been discussed in broad terms; in brief, however, several of the key factors that made Lean manufacturing become such a huge success are less obvious in NPD. One of the most fundamental differences is the conception of value, which in manufacturing can be materialized by systematically eliminating wastes in the process environment around a physical product [3]. On the other hand, the work product in NPD is information which has a much more complex value conception since wastes are less obvious and the value potential is not fixed. Therefore, the opportunity to finding better solutions to solve customer problems makes NPD more value-driven than waste-driven. Hence, the lean concept when applied in NPD is more principal by nature, making it less tool-oriented and with a significantly higher threshold for successful application. As a consequence, there is no common perception in the literature as to what lean in NPD is; the various definitions cover the entire scale from lean manufacturing tools [4] to methodologies for improving efficiency in NPD [5], considering lean as the outcome, to using the lean label on practices that have little to do with the its principles [6].

Owing to the inconclusive definitions of lean and the lack of thorough studies covering its application in NPD and Systems Engineering (SE), the present paper aims to give a contribution to the understanding of practical implementation of lean methods in engineering office functions. The more important research within this field (LSE) has been due to Oppenheim et al. [7] who developed a set of 194 lean enablers that is linked to six basic lean principles. The major contribution of their work is undoubtedly identifying the 'whats' associated with LSE. In the present work, we aim to contribute to the field of research by seeking to touch on the 'hows'. In order to 'peel the next layer off the LSE onion', we designed a case study including a graduate MSc. student team designing, building and launching a fuel efficient vehicle for the Shell-eco marathon competition. The present execution environment is believed representative to simulate real-world situations and different factors present in industrial SE teams, such as knowledge processes in and between product teams, communication practices, strategies for work leveling and task prioritization, product breakdown structure and documentation practices, team leadership, etc. On the other hand, there are also bias factors such as lack of customer pull and commercialization aspects associated with the product.

The conception of value is the single most important aspect of Lean, particularly when this is applied in product development (PD) processes where there is no physical object to which value (or waste) can be assigned. The work product in PD is essentially information that collectively is used to mitigate the risk of launching and producing a product. Therefore, value has to be assigned to information and its aptness in creating *valid* knowledge that is used to resolve problems in a given project, while simultaneously becoming an asset (strategic value) for the company in future projects. Hence, there exist two value streams: the product(ion) value stream and the information value stream. Applying Lean in a SE team, therefore, is very much about creating an environment that ensures 'the right information is available to the right person(s) when needed'. Therefore, strategies to transform, visualize and communicate information are essential to value creation in both a student SE team as an industrial SE team—although their commercial focus is very different—which is the basic idea to elaborated in the continuation. The overall objective of this paper is to establish a generic framework for application of the Lean concept in SE, one that can be converted into a structured approach for implementation with the purpose of generating relevant experience-based information that contribute to the body of knowledge within the field. The following research questions are posted: What are the core components of Lean and how can these become integrated with SE to form an applied model? How can this model be paired with an implementation strategy that emerges from the actual needs of the company or team considered? How to design and perform a case study in the abovementioned execution environment such that the experiences and output can be generalized into a format that could serve as guidance for LSE implementation in companies?

This paper has been organized by first giving a brief introduction to SE and Lean basics. A knowledge-based, lean framework that include six core components has been established along with an assessment tool applicable to prioritize efforts to bridge important gaps identified by the SE team itself. The next part describes the case study, including the competition, the team, the process and the structure of the research as well as the assessment tool developed. The succeeding part includes the results in terms of the experiences gained throughout the study, before finally providing the conclusions based on the results accomplished.

2. Theory

2.1. Systems Engineering—some basic definitions

In Systems Engineering (SE) the effort is essentially to reduce the amount and impact of the risks that threaten the system. Lowering the likelihood of errors occurring late in the life cycle is imperative, as the cost associated with removing such errors is high. A statistical analysis performed on projects in the US Department of Defence shows that the cost of removing errors is 500 to 1000 times higher in the latest stages of the life cycle, compared to the initial stages. A study by INCOSE on the return of investment from SE efforts shows that projects using SE principles greatly reduce their schedule and cost overruns [9]. SE is an iterative process. To reach the goal of risk reduction, the systems engineers work iteratively, following standardized working procedures [8].

SE is to an increasing extent performed in a visual manner. This practice is referred to as Model-Based Systems Engineering (MBSE). Friedenthal et al. [10] say *"[a] MBSE method is a method that implements all or part of the systems engineering process, and produces a system model as one of its primary artifacts."* MBSE is an attempt made to standardize the SE efforts by developing a technique for documenting these through models of diagrams and hierarchies, and a way of depicting systems through requirements, functions, system architecture and VV&T activities. A *system model* is a representation of a system in its elements. The system model is used to ensure the system is being developed correctly. In addition, it acts as an introduction to any engineers new to the system. The model may also be designed to describe the system from a user's perspective explaining the operation of machinery, tools or proper conduct in certain environments [10].

2.2. Lean basics—from manufacturing to office functions

The technology and product-driven transformation became the key to the post world war II growth of Japanese companies. Among these companies, Toyota Motor Car Corporation is one of the most successful ones thanks to, among other factors, its well-known production system (TPS). TPS is considered the originator of what we know as Lean Manufacturing [11]—an operational process management strategy popularized in the 1980s, focusing on waste reduction in the factory ([12],[13],[14]). The term Lean Production was introduced in the late 1980s, describing an approach that used less of everything and doing it faster and cheaper than traditional production techniques. In 1990, Womack et al. [12] published their famous book *The Machine that Changed the World*, which covers a set of techniques under a common heading used to explain the success of Japanese auto manufacturers. Many of the techniques were already well known at that time but looking at lean as part of an overall production strategy was new—and somewhat confusing since there was no recipe as to how to apply it in practice. TPS or Lean is today the benchmark for competitive manufacturing throughout the world. Paradoxically, due to its widespread application, the role of Lean Manufacturing has lately shifted from being a competitive factor to becoming a commodity.

Exploring new ways to gain competitive advantage, a number of companies (and management consultancies) have made attempts to move lean practices from the production floor to other functional areas such as NPD. One of the main challenges, however, is the basic differences between a production process and a dynamic, non-linear NPD process. Anyone who is looking into the great body of knowledge that has been created to establish a common strategy for the lean concept applied in NPD could be surprised by the great variety of interpretations on the concept, proposed pathways for implementation as well as associate practical methods and tools to be used. There is after all some consensus among researchers that lean, particularly when applied to NPD, is more of a mindset than a toolkit, see e.g. Womack and Jones [13] who generalized Lean into a set of five main principles. However, the practical usability of a general principle is limited unless it is filled with more detailed content. Although the different 'schools' of lean in NPD cover a large landscape of thoughts, practices and tools, there is at least one common characteristic: a lack of well-documented success stories from outside Toyota.

Taking this argumentation a step further, it could be tempting to suggest that 'leanness' in NPD in reality reflects the desired *outcome* of a set of activities, whose only purpose is to find better ways to satisfy customer needs. Hence, accepting that lean is a characterization of the desired outcome—rather than a stringent application of a set of general principles—there is a direct (inter)relationship between lean and innovation. Since the latter in popular terms can be denoted 'commercialization of knowledge', there are two indisputable core characteristics associated organizational NPD leanness: (1) the identification and understanding of customer needs; (2) the knowledge and capabilities to satisfy these needs.

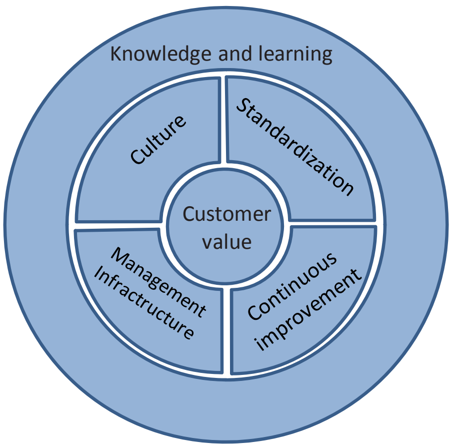
2.3. *A knowledge-based, lean NPD framework*

In the following, a brief description of the different components of a lean NPD framework will be described. It is based on a vast amount of interpretations from the literature, combined with new thinking, views and practices captured from various industrial sources. The following definition expresses the authors' interpretation of lean NPD:

> *"Lean NPD is a holistic philosophy with the goal of continuously improving a company's collective ability to systematically solve problems with basis in—and the inherent satisfaction to generate—new knowledge, driven by customer values and with an outcome that is ultimately desired by the customer".*

The developed model consists of six core components with different (sub-)characteristics which will be presented below. Several models in the literature have a tendency to focus on just a few single components: for example, introducing set-based concurrent engineering and a chief engineer will not automatically improve NPD performance if, say, resources are spent on the project(s) with the lower potential. Other models define a large number of interrelated (sub)components [15], sometimes denoted 'principles', without being mutually exclusive: for example, simultaneous engineering and work leveling, where improving the former will generally lead to better predictability of the needs for resources within different functions, and vice-versa. The present model, on the other hand, represents a suitable compromise between being specific and generic at the same time, aiming to keep an overall system perspective with minimum interdependencies between the different components.

Since the case-study to be presented below is related to the development of a vehicle, a wheel may be used as a metaphor to illustrate the model, see Fig 1(a). The wheel consists of two core components with limited design flexibility: the hub (*understanding customer value*) and the rim/tire (*knowledge and learning capabilities*). The design freedom of the spoke arrangement (the four other core components), on the other hand, will be high to fulfill the functional lay-out of a wheel, meaning that different number, patterns and shapes of spokes may serve the same purpose of providing sufficient structural rigidity and strength for transferring loads while keeping the rim round and in position relative to the hub. Thus, different vehicles ('businesses') used on different roads ('markets') would require different wheel integrity, but each wheel would need a rim/tire and a hub to provide its main functions. In the (figurative) context of LSE, the focus on customer value and knowledge management is key and indisputable, whereas the other four core components are subjected to a great amount of flexibility and customization, depending on the company needs. A more detailed interpretation of the six core components and the underlying characteristics associated with this model in given in [2]



CUSTOMER FOCUS: ROLES AND VALUES — **Underlying question**: To what extent does the company work with the customer to understand current and future customer needs?

Component	Description of the situation: *Low (1)*	*Intermediate (3)*	*High (5)*	Assessment rating: *Current*	*Future*
Perceived role of customer:	Company internal preferences and priorities have usually greater impact on design choices and product specifications than customer needs.	Customer requirements, needs and preferences are generally prioritised but management and design teams sometimes miss important aspects due to insufficient field research in early phases.	'Customer first' is a core value in the company. Every employee views customer satisfaction as the primary driver for future company success, and works continuously to improve customer value.	c_1	f_1
Collaboration with customer in NPD:	Customers/end-users does not have an integrated role in the NPD process. The company has a short-term relationship with individual customers. The company only aims to barely meet predetermined specs and no efforts are made to establish directional product targets together with the customers.	A few customers are viewed as long-term partners and these are to some extent integrated in the NPD process. The bulk part of customers (groups) does not participate actively in the PD process, though.	The customer has a central, integrated role in the company's NPD process to create insight in true customer needs and wants. The company has a very good understanding of their products *from a user perspective,* and uses various methods to continuously extend user knowledge.	c_2	f_2
Integration of customer in continuous improvement of product quality:	Complaints or warranty claims are usually solved at contractual or legal level. These are usually considered as individual quality issues, more than opportunities to better understand *why* the customer is dissatisfied.	The most frequent and serious complaints and warranty claims are assigned to task groups, appointed at management level, resulting in a suboptimal learning process in the organization.	Complaints and warranty claims are used systematically as a source of knowledge for developing better and more desirable new products, as well as improving existing ones.	c_3	f_3
	Average score, *C* and *F*:			$\frac{1}{3}\sum c_i$	$\frac{1}{3}\sum f_i$
	Average gap, (*G*):			$G = F - C$	

Fig.1. (a) s knowledge-based model for the application of the lean concept in SE; (b) exhibit of an assessment sheet for underlying characteristic, value and role of customer in SE, associated with core component customer focus.

3. The Case Study

3.1. Shell eco-marathon in-brief

Shell Eco-marathon is a competition which challenges student teams from around the world to design, build and test energy-efficient vehicles. The competitive element is the energy consumption converted into gas milage measured in petrol equivalents (km/l), where the winner in each class is the team that goes the furthest using the least amount of energy. The concept has its roots from a competition held by engineers at Shell in the US back in 1939. The modern version of the competition started in Europe in 1985, while NTNU has participated since 2008. During this short period, the NTNU project team has experienced several high moments but also a few low ones; for example, the 2009 team set a new world record of 1,246 km/l in the Urban Concepts class using a hydrogen-powered vehicle, the 2011 team finished second in the same class, whereas the 2010 team did not make it to the starting line. The latter is somehow related to the research reported in this article; digging beneath the surface of these overall strong results, the different teams have faced the same problems as many SE teams in the industry; that is, the problems not identified and properly resolved during development come to the surface late in the process, sometimes during field testing at the very end, causing design re-loops, time constraints, corner cutting, reactive problem-solving and ultimately a less-than-optimal product that lacks the desired robustness.

3.2. The DNV Fuel Fighter 2 team

For the 2012 competition, it was decided that the NTNU team will compete in a new category: the so-called Battery-Electric class using Lithium-ion batteries as energy source. This class is more competitive and prestigious than the hydrogen-class which the previous teams had competed in. Hence, the 2012 team is designing and building an-all new vehicle, called the DNV Fuel Fighter 2 (DNVFF2). This is a big challenge with much higher technical risk as compared to improving an existing vehicle, which did the 2009-2011 teams. In addition, extending the team to 14 people (previously 6), from different engineering disciplines for the new concept, represents a considerable managerial risk. Therefore, it was decided that the 2012 team would include two systems engineers (SE1 and SE2), whose responsibility was to focus on the system in its entirety rather than the engineering tasks associated with the individual subsystems and components. The responsibility was split between the two by assigning SE1 to verification, validation and testing, and SE2 to implementation of LSE with particular focus on the up-coming transition from the 2012 team to future teams.

The executing environment consists of a multidisciplinary team with graduate MSc. students from different faculties, including engineering fields such as mechanical, materials, cybernetics, industrial design, electrical, etc. One particular challenge is to manage knowledge transfer in an execution environment with 100% turn-over (a new team every year). The student project is divided into two phases, one for fall semester and one for spring semester. Typically, the fall semester is spent doing concept exploration, evaluation and design of solutions as a part of a mandatory project work at NTNU. The following spring semester is spent doing part production, verification, validation and testing fulltime as a part of their MSc thesis. The subsystems were designed and developed concurrently. For example, the process of integrating body and motor involved numerous iterations and resulted in an overall good quality product. Production was also done in parallel, providing subsystems finishing at approximately the same time.

3.3. The 2012 competition

The 2012 Shell Eco-marathon competition was held at Ahoy Arena in Rotterdam, Netherlands, May 16th-19th. The official length of the track is 1,630m (approx. 1 mile). Each competitor has four attempts. For every trial the vehicle had to complete 10 laps in less than 39 minutes. For every lap the vehicle had to make a full stop at the starting line (launch). In the competition, the DNVFF2 made two successful attempts finishing 5th place in the Urban Concept category with a result of 1,581 km/L, making it the second best newcomer in that class.

Overall, the team did not reach all its goals. The new motor was not finished on time due to a series of repeated production errors, so the team had to compete with the old motor. The team had been proactive in foreseeing the problem and designed the vehicle to also fit the old motor; a strategy associated with set-based concurrent engineering (SBCE) within Lean product development [16]). The team learned that the vehicle with its 87 kg is lighter than all its competitors', and it is mechanically superior. However, it has a less-than-optimal power train, one that would not have been much better with the new motor. Since the vehicle uses most of the energy during launch, it needs a more efficient drive train to win the competition. An extra motor just for acceleration is recommended along with a transmission to increase the torque delivered. Optional solutions for mechanical energy storage will also be investigated by future teams.

4. Research Structure

4.1. Process overview

An overview of the different steps in the case study is listed in Table 1, including six main phases. A considerable amount of time was used to create awareness and knowledge about LSE fundamentals within the team. This was followed by steps of involvement, by having the team themselves decide on the areas where they need to improve and with what means. Individuals were assigned with responsibilities for using the tools, progress and follow-up.

Table 1. Activities undertaken during the course of the project.

Activity	Format	Lead	Participants
Phase 1: Sensation			
Presentations and learning events. Main project sponsor demanded a more seamless transition between teams. Main focus was to improve the team, and to add continuity to the project.	Workshops Assessments	SE1	Team
Phase 2: Preparation Team introduced to Lean Thinking through lectures. Assessment of team's lean practices.	Lectures Meetings	SE1 SE2	Team
Phase 3: Detail planning			
Results were communicated on team meeting, presented on A3. Time frame 4 months. Concrete goals for knowledge management were to employ system modelling, learning events and K-Briefs. Visual Workflow Management (VWM) was to consist of Stand-up meetings.	SE plans, implementer feedback	SE1 SE2	Team
Phase 4: Implementation			
Spiral process. Feedback gathered through interviews. Methods continuously adjusted and tested.	Interviews Meetings Observation	SE1	Team
Phase 5: Validation			
VWM had a great effect on the team the more hectic the situation. Validated in a post-assessment to determine reduction in gaps in fields of focus.	Observation Assessment	SE1	Team
Phase 6: Evaluation and Reflection			
Post review and preparation of input to 2013 team. Overall: Communication is key. Get the whole team on-board before starting the project. Basing project scope on assessment is a good way of getting everyone on-board. Gather feedback continuously. Arrange learning events.	Meetings Lessons events	SE2	Team New Team

4.2. Lean assessment

A questionnaire for assessment of LSE with basis in the model presented above has been developed. The main objective is to identify and prioritize areas for implementation of lean practices in SE. The main structure includes the six components from the framework supplemented with underlying characteristics. Each individual component (from the model) is divided into from two to five underlying characteristics (totally 22). An example of an assessment sheet for one of the underlying characteristics (related to core component *customer value*) is illustrated in Fig. 1.(b). Each underlying characteristic (heading) is divided further into three sub-characteristics representing situational descriptions to which the assessment is done using a Likert scale 1–5. The rating includes both the current (*C*) and the desired (*D*) state based on the specific conditions and environment. The situational description serves as guidance to help make an objective rating based on the three sub-characteristics. On the basis of the assessment, an overall gap (*G*) is estimated for each of the sub-characteristics. The assessment is done on an individual basis, while the final 'score' for each characteristic is based on a team decision; in case there are large gaps between the opinions of the team members, a discussion is made to reach consensus. Final prioritization and implementation strategy are established based on comparing the gaps identified for all characteristics, evaluating these up against efforts and urgency as to whether the gap of the actual characteristic is a limitation (bottleneck).

4.3. Focal areas and implementation strategy

Two assessments were held with the entire team. The purpose of the first assessment (January 2012) was to prioritize focal areas for implementation of LSE. Since defining customer value is key in any LSE effort, the team initially discussed who the customer of this project really is. It was concluded that the team themselves are the ones who will shape their careers on the outcome of this project, thus possessing the unusual situation of being both developers and customers at the same time. The main sponsors were considered stakeholders, not ultimate customers, even if they pay the bill in the end.

For the gap between current and desired state, a threshold-value of G = 1.5 was used to initiate implementation actions. Not surprisingly due to the unusual customer situation, the team did not identify large gapes within any of the characteristics associated with *customer value* (G = 1.0). The assessment results pointed very clearly to a lack of *knowledge* capture and sharing within the project. Especially with concern to team transitions, where no other knowledge is transferred but a MSc thesis—a paper written to satisfy a sensor, not to inform the next year teams. The team estimated gaps that called for actions within four of the characteristics associated with knowledge (G =1.8; 1.6; 2.6; 2.2). In addition, the assessment results indicated that the team did not feel they had good enough control over project progress. The first assessment also concluded on a large gap (G = 2.3) for one of the characteristics within the model dimension *continuous improvement*.

The second assessment was done after the competition (May 30th, 2012) in order to quantify the team's adaption of LSE, particularly within the fields that had been prioritized during the implementation efforts. The result was remarkable; in four out of the five areas, the gaps were reduced between 50-70 %, and only the characteristic related to the use of set-based concurrent engineering (SBCE) was still at the threshold-value G = 1,5 (20 % improvement).

5. Results

5.1. Knowledge management

The results of the lean assessment pointed to a strong need for storing knowledge in an easily accessible fashion, and presented in such a way as to make the learning as desirable as possible. Mascitelli [17] recommends using the A3 Knowledge Brief, and based on his suggestions a set of templates was designed for DNV Fuel Fighter 2. He further states that knowledge must be collected as it is created, and in a standardized fashion as to streamline the process. He points to important data that should be stored for future reference. This is data that has the best long-term utility for an organization—being the type of data that withstand the decay of time—with a strong focus on documenting the decisions made and the reasons behind them.

Not all of these data are relevant to this particular project, though. From discussing with the team members, the following subset of data was agreed upon: Important design trade-offs and decisions; Reusable design elements; Raw material/component data; Test results for common design elements; Reliability data; Supplier design rules/capability data. In addition, the team wanted to have a simple, visual overview of interfaces and risks. The result is a template for a three-page K-Brief which covers all these points, meant as a hand-over to the new team inheriting the vehicle. The first page was dedicated to a break-down into components, their interfaces, important design trade-offs and decisions, reusable design elements, reliability data and supplier data. Components were listed in a table, with columns for weight, dimensions, info on whether the part was developed by the team or purchased, and satisfaction level. Interfaces were shown in a N2-diagram, and a table listing the requirements for main interfaces.

The second page was dedicated to analyses, e.g. structural analyses in CAD. This page gives the reader an overview of how the parts are dimensioned and what situations they are designed to handle. Requirements would typically be listed here, and visual figures are always important. The third page was dedicated to risk analysis, a summary of how the sub-system performed, and ideas for improvements or pointers on where to continue the effort.

The risks were shown in a table, in descending order of magnitude.

5.2. System model

After implementing methods for capturing knowledge, the team will be facing a new issue as the amount of K-Briefs will be growing; the question is then how to store the documents in a robust and easily accessible manner. The team adopted Model-Based Systems Engineering, proposing a combination of the two disciplines; a complete system model, describing the system-of-interest and acting as a portal to the knowledge database. The idea is to link documents to the system elements which they describe.

The idea of using MBSE came from [10], which can be summarized as: enhanced communication; reduced development risk; improved quality; increased productivity; leveraging the models across life cycle; and enhanced knowledge transfer, which comes about *"through the capture of legacy designs, and efficient access and modification of information"* [10]. In [18], C. Haskins adds that "*MBSE improves knowledge capture and reuse leading to reduced cycle time*" and that it improves the "*capacity to teach and learn SE, to integrate new team members, to minimize loss of knowledge as team members leave [and] to establish shared mental models*".

MBSE appears to fit the bill perfectly for DNV Fuel Fighter 2. Consequently, a system model consisting of three, interconnected levels was built; requirements, functional analysis and system architecture (component tree). The levels were connected in the following manner: a function satisfies a requirement, and is realized by a component. A component is associated with a requirement, and is the realization of a function. The important thing with this model was to make it human-readable. Thus, alternatives such as SysML were discarded, which the team perceived as too complex for this purpose. The system model employs boxes and arrows, breaking everything down into hierarchies which are easy to understand. The functions were described with so-called Functional flow block diagrams (FFBDs), which represent functions as boxes, their flow is shown by arrows and summing gates (alternative or parallel flow paths), and input and output are shown as ellipses between the functions.

It was also important for the team to describe the environment where the vehicle was to operate, with special care taken to the race, transportation, track analysis, competitors and team organization. K-Briefs, CAD files, spreadsheets, images, reports and other documents were then related to the system elements which they described (often more than one). CAD files were related to the components they contained, documents containing calculations for the specification of requirements were linked to the requirements they helped specify, and so on.

5.3. Visual workflow management

To help the team regain lost time, and to become aware of actual progress, the team employed Visual Workflow Management (VWM). The goal was to visualize the progress both on a system and detailed levels. Also, the team wanted to be able to discover problems early, and to fix these on the go. To achieve this, three methods were utilized. One of these is well-known in Lean, while the two others were products of creative thinking in the SE team. The three are referred to as *Stand-up meetings*, the *Timeline* and the *Wall-Architecture* (or, just the Wall).

The Timeline is meant as a tool for tracking and visualizing progress on a system level. The idea is a race; every sub-system of the vehicle was represented by a magnet on a long whiteboard (3m). Each sub-system had its own swim-lane horizontally along the whiteboard. Vertically, the whiteboard was divided into weeks. For each week, the main tasks of each sub-system were listed. In the weekly status meetings, each team member would update their sub-system(s) by moving the magnet relatively to how many of their tasks had been accomplished. This tool helped the team identify sub-systems that were lagging, and also the cause—e.g. unbalanced resource allocation, supplier issues, or even team members not pulling their weight. The strategy of having each responsible member update the board on the weekly meetings imposed a sense of urgency and gave the member a chance to highlight problems.

The next method employed, was Stand-up meetings—a well-tested, commonly used method from lean thinking for coping with a dynamic environment. This method was intended to give the team better control over the progress on a day-to-day basis. Mascitelli [5] describes the Stand-ups as short meetings with a duration of maximum 15 minutes, where each participant answers three questions; what has been accomplished since last time, what must be done by next meeting, and what is preventing progress? The ideal frequency is three times a week, but this should be adjusted according to need. Location is unimportant. Furthermore, it is recommended using a dedicated whiteboard for these meetings, so-called Visual Project Boards (VPBs). On this VPB every participant has his or her tasks listed for the next two weeks, with due dates. Tasks that are overdue are highlighted with colors, depending on severity.

A tailored VPB was designed for the DNV Fuel Fighter 2. The meetings were held three times a week in the workshop. The team took a few weeks to get accustomed to the habit of Stand-ups, especially with answering the three questions without digressing. Also, some of the members were more critical to these meetings than others, and felt they were waste of time. The systems engineers would time the meetings, they would switch between participating and just observing and asking questions, and the location would switch between the workshop floor and the office two floors above. Through observing the team, the systems engineers concluded that for the workshop environment the meetings should not last more than 12 minutes, and have no more than 8 participants. Also, answering the three questions is much more efficient than speaking freely. Location was important, as moving up to the offices was undesirable to the majority. The meetings did not really show their worth until the competition: The days were hectic, and the first days were chaos. After implementing Stand-ups, the situation changed dramatically.

The Wall was a method that utilized output from the System Model. The system architecture— a hierarchy showing all sub-systems and components of the vehicle—was printed on A3 sheets, and posted on one of the walls in the workshop. Colored sticky notes would tell whether the component was 'in production', 'pending', 'delayed' or 'produced'. Sub-systems could also be flagged as 'assembled', meaning all components were produced and also fitted to the vehicle. On the sticky notes, the one posting would write messages, e.g. "waiting for more aluminum" or "need help with this one". The team members would update the Wall whenever the situation changed. The system engineers and the project manager would visit the workshop daily to look at the Wall for progress updates.

5.4. Lessons learned – overall results

The K-Briefs are a visual and simple way of structuring knowledge, which is attractive to the reader and easy to learn for the writer. All feedback given on the K-Briefs is positive, and all parties wish to maintain this practice. The system model was also well-received, but it is a bit harder to grasp at first as the users must get familiar with this way of presenting information before the benefits become clear. Functional descriptions are still difficult to understand, even in a simpler format than SysML; however, this experience be influenced by the limited complexity of the DNV Fuel Fighter system, which is mainly mechanical. Functional analysis may be better suited for software development, or for systems with more complex control systems.

In order to be able to address issues early, the project progress must be monitored from more than one perspective. The different methods employed in this project allowed the team to allocate resources as required. The Stand-up meetings proved to be particularly important in urgency situations during the competition, and this is a method which apparently works just as well as described in the literature—even though it take some time to master. However, Stand-up meetings must be performed right and on terms of the team members. The Timeline and the Wall also showed to be useful, particularly for the systems engineers and project manager. For future DNV Fuel Fighter projects, the team concluded that these two tools should be mandatory.

5.5. Critique of methodology and generalization

The major question that arises with regard to the present methodology is whether or not the results are scalable to the commercial world. As already mentioned, the execution environment is somewhat atypical in terms of customer and commercial aspects, which means that challenges associated with these have not been fully explored. Notwithstanding, the work product in any SE effort is essentially information whose value is related to its suitability in creating valid knowledge—one that in turn is used to solve instant problems within the product(ion) value stream of the project and, in a strategic perspective, to solve future problems within the knowledge value stream of the operation. Since all approaches is this study are concerned with the generation, transfer, communication and (re)use of information within a team, it is believed that multiple aspects associated with the results are relevant to team practices in a more general perspective, no matter the pull comes from the desire to succeed in business or in an eco-car student competition. However, the actual performance improvement numbers in terms of bridging gaps should be seen in relation to an easy-to-follow execution environment without too many external 'disturbances' as would be the case in a real-world study. In this perspective, the efforts made herein may be seen as an *accelerated test* (resembling corrosion testing of materials), adapted to provoke fast results under controllable conditions. Like accelerated corrosion tests, the methods have proven that they do have impact, and some more than others, while the time scale for obtaining results is still uncertain. Hence, the present results have directional and relative merits, whereas 'in-situ field testing' is necessary for final validation.

The results showed that K-Briefs are a good way of capturing knowledge; how to manage an ever-growing database efficiently remains a concern. Any company who considers introducing this tool must develop a strategy and practices to address this issue from the beginning. Introducing (new) K-Briefs as the solution to any problem is wishful thinking without establishing strategies to improving, maintaining and using the data base. Using system models created through MBSE efforts was this team's way of handling this issue. MBSE is a method that is still unproven and lacks success-stories. Its application may be growing; however, it must be taken as a somewhat premature approach, still waiting for its breakthrough. The practices of VWM showed much promise for other short-duration projects reminiscent of this student project. The shorter the project, the more precious is the time and good practices become increasingly important. The Timeline and Wall need to be explored further in future research.

Knowledge management is an important concern, especially in environments with high turnover of people. The practical applicability of system modeling is strongly dependent on investment level. Building a comprehensive system model (SM) is expensive, and for a short-duration project it may not be a healthy investment. The use of SM must be conveyed with respect to the duration of the project, its complexity and the actual scope. If a company wishes to learn from every project, SM is a suitable approach for documenting the process and results.

6. Conclusions

The present work presents the structure of a generic LSE framework that comes with an assessment tool and a strategy for prioritizing focal areas to best fulfill the actual needs of different companies. The framework consists of six core components with underlying characteristics that can be adapted to the project environment of various SE teams. Its practical use has been demonstrated through a case study including a multi-disciplinary student team designing, building and validating an energy efficient vehicle. The case study revealed that LSE dimensions *knowledge management* and *continuous improvements* were the ones with the larger gaps for this specific team. The implementation actions conducted to bridge the larger gaps by applying methods such as K-briefs, visual work flow managements, stand-ups, model-based modeling, etc. Systematically assessing the larger gaps before and after implementation showed dramatic effects of LSE methods. With a somewhat unusual setting of commercial and customer aspects present, there is factor bias associated with the scalability of the results to an industrial company. However, since the research efforts concerned transformation, communication and visualization of information—which are essential to value creation in LSE teams, these being driven by business aspects or not—it is suggested that the potential of the LSE tools has been made evident though the case study reported herein.

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