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APPLICATION OF INDUSTRY RECOGNISED DEVELOPMENT TOOLS AND METHODOLOGIES, SUCH AS SIX SIGMA TO FACILITATE THE EFFICIENT DELIVERY OF INNOVATIVE AND ROBUST ENGINEERING SOLUTIONS AT SYNCHROTRON FACILITIES

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Abstract

Synchrotron facilities play a key part in the delivery of world leading science to facilitate research and development across multiple fields. The enabling technology designed by engineers at these facilities is crucial to their success.

The highly academic nature of Synchrotron facilities does not always lead to working in the same way as a commercial engineering company. However, are the engineering requirements at Synchrotrons different to commercial companies? Exploring the parallels between research and commercial companies, can we show that the tools and methodologies employed could benefit engineering development at Synchrotrons?

This paper provides a theoretical discussion on the commonality between engineering developments at Synchrotron facilities compared to commercial companies. How methodologies such as Design for Six Sigma and in particular tools such as stakeholder analysis, functional tree analysis, FMEA and DoE could be utilised in the design process at Synchrotrons. It also seeks to demonstrate how implementation could aid the development of innovative, robust and efficient design of engineering solutions to meet the ever-increasing demands of our facilities.

INTRODUCTION

Diamond Light Source [1], as other Synchrotron facilities around the globe, generates brilliant beams of light from infrared to X-rays, used for academic and industrial research. This research can be at the cutting edge of scientific discovery and therefore requires innovative enabling technology, engineered to meet unique requirements. Diamond Light Source like other facilities is a 'not for profit' organisation that is primarily government funded.

Commercial companies, on the other hand must develop innovative products that meet the needs of particular markets. Markets and the opportunity they present are constantly changing and companies must adapt and develop new innovative products and technology to meet these ever-changing needs. Commercial companies operate to make a profit that can fund business growth and the development of next generation products.

Synchrotron facilities and commercial companies operate and are funded differently, but at the heart of both of these organisations is a need to develop new and innovative solutions to meet unique engineering requirements. The ability to deliver to these unique engineering requirements determines the success of the organisation whether it be a Synchrotron facility or a commercial company.

Many commercial companies utilise Six Sigma approaches within their organisations. The many success stories of Six Sigma implementation include organisations such as [2] GE, Motorola, Honeywell, Bombardier, 3M Ford and Toshiba. Today, many large commercial organisations have implemented Six Sigma and are reporting large profits.

However, implementation of Six Sigma is not common at Synchrotron facilities. Given the funded research nature of these types of organisation, and headlines of profit associated with Six Sigma it is perhaps possible to understand why. Six Sigma also holds a statistical association that implies it is only useful for organisations creating products for mass production. This does not necessarily match with the single unique engineering developments carried out at Synchrotrons.

However, when we explore the Six Sigma methodology further and how and why it is used. We can see that the use of Six Sigma within an organisation can provide systematic approaches to process improvement, problem solving of existing designs and improve quality in new design

Since Synchrotron facilities utilise processes, can have a requirement to solve problems and do require high levels of quality in the design of their systems it is hard to believe that the Six Sigma approach or at least parts of it would not be beneficial. In fact, if we were to deploy some of the tools embedded in the Six Sigma approach at Synchrotrons could we save time in development, could we improve the performance and ultimately increase our ability to deliver world leading scientific research?

At Diamond Light Source Ltd, we have started to investigate the Six Sigma methodology and how we might apply this to the benefit of our organisation.

ENGINEERING DEVELOPMENTS AT SYNCHROTRON FACILITIES VERSUS COMMERCIAL COMPANIES

If we strip away the input and output factors of any engineering organisation, we see that there is a core process

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of converting requirements into solutions. This common ground at the heart of an organisation, be it a Synchrotron facility or a commercial company, demonstrates that however the organisation is funded or whatever its final output is, there are some aspects of these organisations that must be similar.

At a Synchrotron facility, the requirement to do some engineering development may originate from a scientific need to allow specific research to be undertaken. In a commercial company, the requirement may originate from the feedback of customers within its operating markets. Ultimately, irrespective of the origin or detail we have identified a 'need' to do some engineering development.

At a Synchrotron facility, there may be a requirement to satisfy this need in order that research can be completed and published first. In a commercial company, there may be a requirement to satisfy this need in order to hit a market window and release a product ahead of its competitors. Both of these scenarios demonstrate a requirement for needs to be satisfied within certain timescales to ensure success. Although at a Synchrotron, the timescales aspect may not be as critical due to the many unknowns associated with carrying out scientific research, delays to enabling the research to take place could mean another scientist somewhere round the world could undertake this first.

From identifying a requirement or need, we need to translate these into a specification detailing what it is we actually need to engineer. Requirements and specifications are fundamental to ensuring an agreed understanding of the criteria an engineering solution needs to meet in order to be successful. Failure to do this means that project scope may creep, designs may not be fit for purpose, the project may overspend and there may be substantial delays in the time taken for the development. For either type of organisation, this can have detrimental consequences. Therefore, delivery on time, to specification and in budget is critical to both.

As engineers, we all want to ensure whatever solutions we deliver, perform at the correct level. Requirements and specifications become critical in ensuring we define what the correct level of performance is; in fact, they allow us to define what success looks like.

The actual requirements and specifications at Synchrotrons and commercial companies may be very different in terms of content or priority; however, they still define the criteria against which the development activity will progress.

The phases that engineers may go through in development of solutions can include; concept generation and selection, detail design, prototyping, manufacture and assembly, testing and verification. All of these steps ensure we develop solutions that meets the criteria specified in our requirements and specification documents. In other words how we deliver a solution of the correct quality to meet the required performance standards.

These phases may look very different depending on the type of organisation. For example, at a Synchrotron where we are generally designing and building a one-off solution, any prototype hardware may in fact be the hardware used. Testing and verification may happen on this during installation and commissioning phases. In commercial companies where they intend to sell quantities of a product, they often manufacture several sets of prototype hardware. Each set of prototype hardware tests different aspects in terms of performance and the processes involved in mass production, particularly repeatability and reproducibility.

At a commercial company, issues with quality, cost or timescales could lead to a product that does not meet the needs of the market, higher operating costs, reduced profit and missed market windows. Ultimately, the company may lose customers and market share, severely affecting their bottom line.

For a Synchrotron issues with quality, cost or timescales could lead to solutions that are unable to facilitate some or all of the science they were required for, missed opportunities to deliver ground breaking science and delays in availability of resources to do other developments. Ultimately, this could mean cancelling users, a reduction in publications and possible loss of future funding.

Acknowledging that there are differences between these types of organisation we have also shown that the aspects of cost, time and quality apply to both. Therefore, it seems that it should be possible to use the Six Sigma approach or at least some of the tools encompassed in this approach to ensure that we are meeting the quality, cost and timescale requirements at a Synchrotron facility.

SIX SIGMA OVERVIEW AND USEFUL TOOLS

Overview

Six Sigma [2] has been around in its current form since the late 70s when Motorola developed the approach and documented savings of over $16 billion [2]. Six Sigma has a foundation in statistics and the idea that the nearest specification limit is six standard deviations from the mean, then as the variation in a process increases the mean, the result will move further away from the midpoint of the specification limits. Consequently, fewer standard deviations will fit between the mean and the specification limit.

This statistical approach is also why it can put off organisations such as Synchrotron facilities as we may only have a data set of one.

However, when we look further into Six Sigma there are two fundamental methodologies associated with Six Sigma, DMAIC and DFSS.

DMAIC [3-5] is the most commonly used methodology and is mostly concerned with existing processes or hardware that are wasting resources. DMAIC stands for Define, Measure, Analyse, Improve and Control. In essence, define the requirements or project goals, measure current performance, determine root cause, implement corrective actions to eliminate the root cause issue and implement controls to ensure continued good performance.

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DFSS [3, 4] on the other hand stands for Design for Six Sigma and is concerned with the design of a new product for Six Sigma quality. Unlike DMAIC, there are several different ways to approach Design for Six Sigma. The approach implemented at a company will depend on the type of business. Therefore, we can consider Design for Six Sigma more of an approach than a defined methodology.

As an Engineer, you can approach Six Sigma in the same way as your toolbox. Your toolbox can hold multiple tools, you do not always need to use every tool in the box for every job that you do but you do need to use your tools in the right order. Using the right tool, at the right time allows you to complete work efficiently and successfully.

Selecting and applying appropriate tools from within the Six Sigma framework and applying to development activities at Synchrotron facilities should offer improvements to the quality and efficiency of delivery.

Stakeholder Identification

When it comes to defining, the requirements for a new development at a Synchrotron facility there are many stakeholders and these can be both internal and external. Stakeholders are those people who will benefit from the project, people impacted by the project, people who will have an interest in the project and those who may have a concern regarding the project. These may be our users, members of peer review panels, senior management, engineers, scientists, specialist groups, suppliers or even partners at other Synchrotrons. Brainstorming whom the project will touch and identifying interfaces where exchanges of information or materials may occur will support developing a list of stakeholders for a project.

An Elliot Kemp Matrix [4-6] can be utilised to clarify who our stakeholders are in terms of their power and influence and their interest or concern in the project. Figure 1 shows how the Elliot Kemp matrix is constructed, with quadrants representing the different types of stakeholder. Those in quadrant 1 are key players, ready and willing to participate in the project. Quadrant 2 represents those stakeholders that would be willing to participate if they could but lack required knowledge or power. Quadrant 3 have an ability to influence the project but do not want to engage. Finally, quadrant 4 are those with no influence and minimal interest in the project.

The success or failure of a project can hinge around engaging with the right people at the right time throughout the project lifecycle. Particularly, when we consider the specialist nature of Synchrotron facilities. We are endeavouring to do things that have potentially never been done before and in order to succeed we need to engage with and have people engage in supporting us. Understanding, of who these people are and how we need to involve them can only benefit us. How often have you done months of work to find there is a problem with your solution due to something you were not aware of, perhaps there was a stakeholder missing from initial project discussions that could have made you aware earlier?

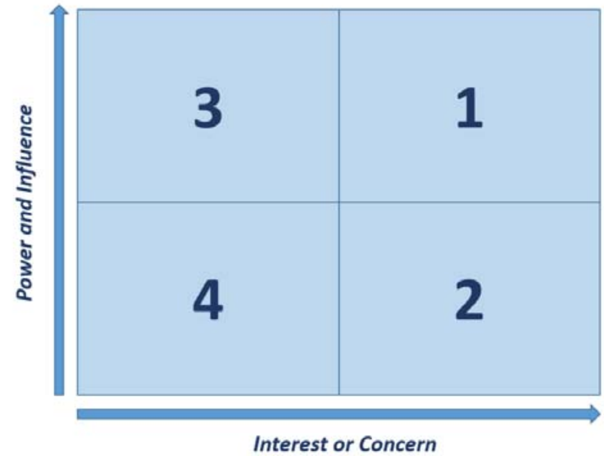

Figure 1: Elliot Kemp Matrix.

Engaging at the right level with stakeholders throughout a project can ensure that requirements, specification, design solutions and decisions are effective, preventing the need for rework because of missing information or knowledge. This can be of particular importance at a Synchrotron were there are a plethora of specialist groups with specialist knowledge.

Functions Identification

Describing the hardware we want to design by its functions, can prevent constraining elements becoming fixed in the design [4, 5]. The concept of functionality means we describe something in terms of what it does rather than what it is. Describing a design in terms of its functions and not its solutions enables us to determine design criteria, which helps us, develop the requirements specification and ultimately encourage innovation.

We could view this, as a method to get inside the head of the scientist and facilitate understanding as to what it is they want.

To do this we describe functions using two words, a verb and a noun. The noun in this case must not be part of the hardware. So for example, in designing a beamline we might say it needs to illuminate a sample, we might say it needs to generate light or provide energy; we might talk about aligning sample or presenting sample. Ultimately, we want to describe all the functions required to achieve the end goal of the scientist, starting with the top-level function or 'Task' function.

Figure 2 is an example of how from the task function we can define a functional structure or functional tree for the system we are designing. The task function sits at the top of the tree. From this starting point, you develop the next level of functions by asking 'How' we can achieve the task function. This cascades downwards until we reach the lowest level of functions. The overall size of the structure will depend on the complexity of the system.

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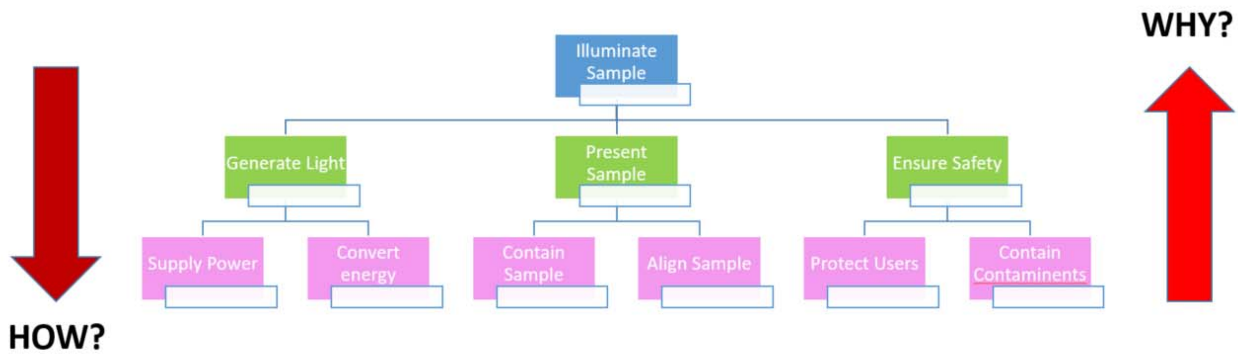

Figure 2: Example Functional Tree.

Progressing down the functional tree shows how to achieve the function above, progressing up the tree shows why we need the function. I.e. we need to 'Protect Users;' Why? To 'Ensure Safety.'

Once a functional tree is established, it can help guide the development, aiding prioritisation of functions delivery and more importantly defining specifications. For example, we want to align a sample. What accuracy or resolution is required?

Use of functional trees to aid in requirements capture is being trialled at Diamond Light Source and whilst we are refining the process to suit us, this technique is proving successful and we are looking to use this more in the future.

FMEA

Finding design problems late in the development process can cause substantial disruption to a project. Particularly, in Synchrotrons where some work may need to done in 'shutdown' periods. This provides a small window of opportunity for work to be completed and everything needs to be ready on time and without faults.

Risk analysis offers us the opportunity to proactively identify errors and take action in time to avoid them. FMEA [4-6] or Failure Mode and Effect Analysis is an industry standard method of carrying out risk analysis. It presents a systematic approach to establishing failure modes, effects and potential causes. FMEA is a continual process throughout the development cycle. A Systems FMEA completed following specification agreement but before design, allows us to mitigate issues ahead of creating and selecting design solutions.

A Design FMEA allows us to assess risk of failure with respect to the design solution and occurs after a concept solution is proposed and prior to detail design. This allows us to mitigate risk of failure due to the design throughout the detail design phase and supports assessment of the final design solution prior to manufacture.

A Process FMEA allows us to review things that may go wrong in the manufacturing, assembly, installation or commissioning processes. This should occur following design completion and ahead of the next development, manufacturing and testing phases.

The functional tree created previously allows identification of failure modes by analysing the functions we require. Each failure mode assessed allows us to look at the causes of failure and score them with respect to the severity of failure, the likelihood of occurrence and ability to detect the failure; creating a risk priority number.

Benefits to this method include:

- Early identification of potential problems throughout the lifecycle
- Increased quality and likelihood of being right first time
- Ability to stay on budget
- More efficient delivery, increased likelihood of being on time
- More emphasis on lessons learned and understanding of what has or has not been done before
- Prioritisation of key potential issues early

At Synchrotron facilities where budget is limited, we only want to do something once. There are particular constraints surrounding how and when installation can occur. It is critically important that we mitigate risks and deliver a working system when required. FMEA, particularly the systems level and design level FMEAs could ensure improved quality and improved efficiency in the delivery of working design solutions for our facilities.

DoE

Design of Experiments [4-6] or DoE is a controlled way of exploring the effects of different factors on system performance. In effect, the process allows us to consider different input variables and in so doing, optimise a design or system. For example, we might have a cooling system. Inputs to the system's performance may be the material, cooling fluid, length of cooling channel and flow rates. DoE allows us to understand how these factors and their interactions affect overall system performance and subsequently optimise the design of our system for desired performance. For example, we may want to keep our component below a certain temperature. As such, we may wish to determine the optimum length of cooling channel and flow rate to achieve this. Using DoE, we would systematically plan an experiment that would vary

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these two inputs and measure the results. We can then analyse these results to see which has the biggest effect and how the interaction between these two inputs effects the performance. Ultimately, allowing us to make a decision on the optimum length and flow rate.

At a Synchrotron, the performance of our systems is vital to enable our scientific experiments to continue successfully. If our systems do not perform as expected then the consequence could be that we are unable to carry out these experiments and there could be significant delays and cost associated with rectifying these issues.

DoE is relevant within both the development and operational cycles of a system. For an operational system, it could aid in understanding problem performance; for a development system, it can proactively be used to optimise performance. Whilst this is experimental testing, it does not necessarily mean that this must be tested with physical hardware, under some circumstances and with the correct setup, simulated experiments could also be used, particularly to optimise designs.

Selection and Prioritisation

Engineering development entails making many decisions and many of these decisions relate directly to how well the solution will meet the performance criteria. This can be a difficult process particularly for larger projects with many stakeholders. However, there are a couple of simple techniques that support the decision making process.

The first of which is called 'paired comparison [6].' This is a simple technique, ideal for use in establishing priorities, particularly of design criteria. For example, if we have criteria A, B, C, D, and E. We can compare pairs of criteria in turn and total the winning occurrences of each criteria, i.e. we can compare criteria A and B, A and C, A and D, A and E; asking which is more important.

Table 1: Paired Comparison Matrix

	A	*B*	*C*	*D*	*E*
A		**A**	**A**	**A**	**A**
B			**B**	**D**	**E**
C				**D**	**E**
D					**D**
∑	**4**	**1**	**0**	**3**	**2**

Table 1 shows the results of the comparison of each pair of criteria in red. We can then count the number of winning occurrences for each criteria. The criteria with the highest number of occurrences indicates the most important criteria, in this case A with four occurrences. C has zero occurrences and therefore is the least important. This does not mean C is not important but that we prioritise decisions towards meeting criteria A, with D being the next important, followed by E and then B.

In order to select the most appropriate design solutions a commonly used technique is a Criteria Matrix [6]. This technique allows us to score design solutions against weighted criteria. The development team score each possible solution out of 10 against the design criteria, this is multiplied by a weighting for the design criteria itself and the total weighted score for each solution summed. Highest overall score indicates the solution that best meets the design criteria.

Table 2: Example of a Criteria Matrix

Design Criteria	Weight	Design 1		Design 2	
		Score	**Wtd. Score**	**Score**	**Wtd. Score**
A	10	1	10	5	50
B	4	10	40	10	40
C	2	5	10	7	14
D	8	7	56	3	24
E	6	8	48	1	6
Total			**164**		**134**

Table 2 shows an example of how a criteria matrix works. In this example, the weighted scores for the criteria were determined by giving each criteria a score out of 10 based on the priorities agreed using the paired comparison.

These two simple methods for prioritising and selecting solutions are easy to use and provide a quantifiable process for decision-making.

CONCLUSION

Whilst there are many differences between Synchrotron facilities and commercial companies, at the core, both must meet quality, time and cost targets.

Six Sigma whilst in its full statistical sense may not seem applicable at Synchrotron facilities we do look for continual quality improvement of our design solutions and the improved efficiency of our delivery processes. With the size and specialist nature of our organisations the tools contained within the Six Sigma approach are of definite benefit.

Whilst only a small number of tools have been reviewed and trialled at Diamond Light Source Ltd, we will be continuing to investigate the application of Six Sigma methodologies further.

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