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A3 Thinking Approach to Support Knowledge-Driven Design

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Abstract

Problem solving is a crucial skill in product development. Any lack of effective decision making at an early design stage will affect productivity and increase costs and the lead time for the other stages of the product development life cycle. This could be improved by the use of a simple and informative approach which allows the designers and engineers to make decisions in product design by providing useful knowledge. This paper presents a novel A3 thinking approach to problem solving in product design, and provides a new A3 template which is structured from a combination of customised elements (e.g. the 8 Disciplines approach) and reflection practice. This approach was validated using a case study in the Electromagnetic Compatibility (EMC) design issue for an automotive electrical sub-assembly product. The main advantage of the developed approach is to create and capture the useful knowledge in a simple manner. Moreover, the approach provides a reflection section allowing the designers to turn their experience of design problem solving into proper learning and to represent their understanding of the design solution. These will be systematically structured (e.g. as a design checklist) to be circulated and shared as a reference for future design projects. Thus, the recurrence of similar design problems will be prevented and will aid the designers in adopting the expected EMC test results.

Keywords *A3 Thinking, knowledge-driven design, problem solving, product design*

1 Introduction

Manufacturing enterprises have recognised the importance of creating a knowledge environment to support product development. This is to enhance the quality of decision making through the development process, as well as to re-use and share the knowledge in order to address the different product development

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challenges. During the design process, the designers will encounter different problems that need to be addressed and solved. As such, a problem-solving skill and approach is required to support the design process. The solutions from solving design problems create new knowledge, and such knowledge becomes important in the next stages of the product's development project, as well as for any future project(s). Several researches have addressed the importance of knowledge in product design, design rationale and design intent [1 - 4]; however, these are not related to the theme of this paper which is to capture and share the knowledge created from solving problems that have been encountered in the design process. Therefore, they are not covered in this paper.

Solving a problem in product design will generate two important outputs: the obtained solution and the created knowledge. Three main challenges hinder the full utilisation of the created knowledge. The first challenge is that most designers are more interested in reaching and implementing the solution rather than capturing and visualising the created knowledge in an informative and simple manner that could be useful for current and future projects [5]. Therefore, there is a need for a problem-solving approach that could be implemented during the design stage and that ensures knowledge creation and capture, as well as the provision of a knowledge-rich environment. Such an approach will also contribute to the generation of a better design solution. The second challenge is that there is a need for a mechanism that allows the captured knowledge to be shared with and communicated to other engineers and projects. Due to the high level of competition involved in a product launch, designers have to solve the design problems quickly [6]. Consequently, time limitations and lack of suitable tools can hinder the capture of knowledge generated from the problem solving process. The third challenge is that it is difficult to locate and use the existing knowledge from different sources, such as databases and a huge range of documentation. Such a lack of support for the designer's decision making in utilising relevant knowledge is likely to lead to an increased risk of design iterations. Sharing knowledge among the designers and engineers during product design and development is important, otherwise bad decisions in design will be taken, and the communication barriers among the team will be enlarged [7].

This paper aims to address these challenges by presenting a novel approach to problem solving in product design. The novelty of the approach is in three areas: first, developing a process to solve problems; second, presenting a way to capture the created useful knowledge; and third, providing a simple template as a tool to share and support the communication of that useful knowledge. Within the context of this paper, the authors have defined useful knowledge as knowledge derived from the systematic process, enabling designers to understand the linkage between hypotheses and practice which results in a new learning and understanding. This will enable the designers to solve a problem whilst enriching the environment of efficient knowledge creation and capture to be shared in the future. The combination of these aspects is called the 'A3 thinking' approach, and it aims to facilitate the generation of knowledge-driven design to support decision making and, hence, eliminate design mistakes in future.

Traditional A3 thinking is defined as an approach to solve problems and find opportunities for improvement in manufacturing on the shop-floor [8]. The A3 report was developed by the Toyota Motor Corporation in the early 1960s as a technique to solve problems and provide continuous improvement based on the traditional A3 thinking approach [9]. The A3 report was structured into seven elements: 1) Background, 2) Current condition, 3) Future goal, 4) Root cause analysis, 5) Countermeasures, 6) Implementation plan, and 7) Follow-up actions [10]. These elements are guided by the learning cycle of continuous improvement; Plan-Do-Check-Act (PDCA). However, the traditional A3 thinking approach does not integrate the aspects of knowledge creation, capture and sharing.

To overcome such limitations in the traditional A3 approach, the proposed A3 thinking approach will entail a range of applications to be used in product design, such as design problem solving, idea generation, knowledge communication and visualisation, knowledge reuse for new projects and lessons learned. This range of applications will enable designers to make decisions in a knowledge-rich environment. According to [11], a knowledge-rich environment allows the provision of customer-driven products and services in a fast changing market. This definition, however, seems quite generic and for the scope of this research, the environment of product design is considered as knowledge-rich when it provides potential for the design team to capture and obtain useful knowledge. The latter has either been previously used to solve design problems or been newly created during problem solving activities in the product design.

This paper is structured into six sections: Section 1 describes the research methodology. The analysis and limitations of problem solving approaches for product design are performed and identified by considering knowledge creation, capturing and sharing, and are explained in Section 1. The development of the A3 thinking approach is explained in Section 4. Section 5 describes a case study derived from an Electromagnetic Compatibility (EMC) design issue and finally the conclusion is discussed in Section 6.

2 Research Methodology

The research methodology used to carry out the research presented in this paper has gone through five steps. Firstly, the review and analysis of the literature is covered among several problem solving approaches and those capable of being considered and adapted in product design are identified. Secondly, an inter-relation analysis has been performed within the problem solving approaches. This is to identify the effectiveness of the different techniques and processes that are in use to describe and analyse a problem, which then leads to practical solutions and represents the useful knowledge creation.Thirdly, the limitations of the current problem solving approaches have been identified by considering knowledge creation, capture and sharing.Fourthly, a novel A3 thinking approach has been developed that has been formulated based on the results of the above key tasks by utilising the LAMDA (Look-Ask-Model-Discuss-Act) learning cycle, adopting the reflection practice and developing a new A3 template. Finally, implementation of the A3 thinking approach has been performed in an automotive company in the United Kingdom.

3 Review and Analysis of Problem Solving for Product Design

A product design is a process that indicates the means by which the product will produce the required function [12]. Likkanenand Pertula[13]state that a conceptual design is commonly described as problem solving. From the perspective of industrial design, the literature considering various aspects of the design process indicates that a vital activity of the design process is creativity problem solving [14]. An example of creativity problem solving in design is discussed by Van der Lugt[15] who explores the roles of sketching in design thinking, suggesting that the use of such at the idea generation meeting may enhance the creative problem solving activity.

Problem solving is the process of determining the best possible action that needs to be taken in a given situation which is a complex process activity [16]. Goffin et al. [17] define that new product development as a learning process relies on generating and sharing knowledge, while [18] states that new product development can be considered as a series of problem solving activities where the design solutions are playing a key role in the contribution to knowledge [19]. The role of knowledge in designing a product becomes the primary source of sustainable competitive advantage, identified by short product life cycles and complex processes [20]. Therefore, the design team needs an informative and simple approach to creating, tailoring and sharing the new knowledge. Goffin and Koners[21] state that product design is a problem solving activity that generates tacit knowledge which is difficult to express and share, thereby requiring effective communication among the teams in an organisation. As the problem solving in design becomes a more complex and important activity, this means that the incorporation of the previous knowledge is essential. In a simple state, the idea of the A3 thinking approach to develop a concise problem solving that yields a concise solution should make it easier for the designers to capture and visualise the created knowledge. A concise knowledge visualisation will encourage the designers to obtain useful knowledge in a knowledge-rich environment.

3.1 Problem-solving Approaches for Product Design

An enormous number of approaches to problem solvingexist. The following explains some problem solving approaches that have been or could be used in product design.**Brainstorming (BS)** allows the designers to discuss and explore potential ideas to solve a problem hence, to represent and verbalise their arguments spontaneously [22]. **Theory of inventive problem solving (TRIZ)** is derived from the study of the patterns of problems and solutions [23 - 24]. **8 Disciplines (8D)** is for solving problems in product and process improvement which are recurring [25] and to generate possible solutions for product requirements, conceptual design, detail design, and prototyping[24]. **A3 Report** is created from the A3 template and has been used as a problem solving and effective communication approach in manufacturing and management [9, 10,26 - 28]. It follows evidence and logical structures of the seven elements in sequence, which are separately allocated on the A3 paper based on the Plan-Do-Check-Act (PDCA) learning cycle [29]. **Creative Problem Solving (CPS)** is used to create new ideas for products [30] and to enhance the creative thinking of the design team [31]. **Kepner-Tregoe (KT)** is associated with states shifting from As-If to To-Be [32] which consists of two main stages: problem analysis and decision making [25]. **5 Whys** is to identify the root cause of a problem (ask 'why' five times) [34] and is used in manufacturing operations thus providing a fact based and structured approach to addressing the problem, and reducing and eliminating the defects [35].Fantoni et al. [33]state that 5 Whys is commonly used at the first stage in the design process for design requirements and customer value identifications. **Root cause analysis (RCA)** is designed to investigate and identify the origin of the problems along with fixing them. It is significant in improving the product quality and process productivity whilst controlling variations during the manufacturing process [36]. Doggett [37] states that RCA has also been used for possible issues in design stages and well-identified causal relationships. **Problem Analysis Flowchart (PAF)** is used by using a single sheet and its advantage is that an inexperienced person will be able to understand clearly how to solve a similar problem by looking at the provided template [34].

The potential of five problem solving approaches (8D, A3 report, 5 Whys, RCA and PAF) have been selected by the authors. The reasons are because the full problem solving processes are provided by two approaches, namely 8D and A3 report and applied in product design i.e. 5 Whys, RCA and PAF. Moreover, all these approaches are non-statistical or computational and were developed by utilising a template. The template has become the most preferred method in European manufacturing companies as a mechanism to capture and document knowledge [5]. The non-selected approaches (BS, TRIZ, CPS and KT) could be considered as tools for particularprocesses in the new A3 thinking approach. In order to support problem solving in product design by using a simple template, it is vital to identify which elements are required.

3.2 Analysis of the Problem Solving Approaches

Phase-to-phase inter-relation analysis has been performed for the problem solving approaches as shown in Table 1. This has led to the identification of suitable elements to be used in designing a new template for the A3 thinking approach to support knowledge-driven design, and these are presented in this sub-section.Table 1has five main columns representing five problem solving approaches with their key elements ranging from 8D to the PAF. Each of the key elements illustrates the various recommended tools used in their templates and these are explained as a legend at the bottom of the table. The 8D approach has been selected as a standard, shown in italics, as the authors identified that the 8D is the approach withthe highest performance, as shown in Table 1, and also has the greatest quantity of key phases compared to the traditional A3 report. The rows coloured grey indicate that the elements from the problem solving approaches are not provided. The important findings based on the analysis in Table 1are as follows:

- The key elements used in 5 Whys, RCA and PAF are also used in 8D and the traditional A3 report.
- Key elements 1 (‘Background’) and 3 (‘Future Goal’) in the traditional A3 report do not exist in the 8D approach.
- Key elements 1 (‘Team’), 3 (‘Containment’), and 7 (‘Prevent Recurrence’) in the 8D approach are not included in the traditional A3 report.

From the inter-relation analysis, this paper identified the eight elements that could be applied to solve a problem in product design by using a new A3 template that will support the knowledge-driven design based on the new A3 thinking approach presented in Section 4. The eight final elements that have been selected to be structured into a new A3 template are (1) ‘Team’, (2) ‘Background’, (3) ‘Current Condition’, (4) ‘Root Cause Analysis’, (5) ‘Proposed Solutions’, (6) ‘Implementation Plan’, (7) ‘Prevent Recurrence’, and (8) ‘Follow-up Action’. The

‘Future Goal’ and ‘Containment’ are only considered as a part of the ‘Background’ and ‘Proposed Solutions’ elements in a new A3 template.

Table 1 The Phase-to-Phase Inter-relation Analysis of Problem Solving Approach

<table>
<tr><th></th><th colspan="5">Problem Solving Approaches</th></tr>
<tr><th></th><th>8 Disciplines (8D) Standard</th><th>Traditional A3 Report</th><th>5 Whys</th><th>Root Cause Analysis (RCA)</th><th>Problem Analysis Flowchart (PAF)</th></tr>
<tr><td rowspan="19">Key Elements</td><td>1. Team (f)</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>1. Background (d)</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">2. Clarify the problem (g)</td><td rowspan="3">2. Current condition (d)</td><td></td><td>1. Define the problem (a)</td><td rowspan="3">1.Problem statement (a)</td></tr>
<tr><td></td><td>2. Collect the data (a)</td></tr>
<tr><td></td><td>3. Identify possible causal factors (a)</td></tr>
<tr><td></td><td>3. Future goal (b)</td><td></td><td></td><td></td></tr>
<tr><td>3. Containment (a)</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="8">4. Identify the root cause (c)</td><td rowspan="8">4. Root-cause analysis (c)</td><td rowspan="8">5 Why (d)</td><td rowspan="8">Identify the root cause (a)</td><td>2.Symptoms (b)</td></tr>
<tr><td>3.Changes (b)</td></tr>
<tr><td>4.Relevant data (b)</td></tr>
<tr><td>5.Defect free configurations (b)</td></tr>
<tr><td>6.Distinction (b)</td></tr>
<tr><td>7.Causal chains (g)</td></tr>
<tr><td>8.Test, corrections, results and conclusion (f)</td></tr>
<tr><td>9.Most probable cause (b)</td></tr>
<tr><td>5. Proposed solutions (f)</td><td>5. Countermeasures (f)</td><td></td><td>5. Recommend and implement solutions</td><td>10.Short term and long term corrections and controls (b)</td></tr>
<tr><td>6. Implement permanent solutions(a)</td><td>6. Implementation plan (f)</td><td></td><td></td><td></td></tr>
<tr><td>7. Prevent recurrence (f)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>8. Congratulate the team (Validation)(f)</td><td>7. Follow-up action (f)</td><td></td><td></td><td></td></tr>
<tr><td colspan="6">a = text   c = diagram   e = graph   g = sketch
b = bullet   d = combination   f = table</td></tr>
</table>

In order to ensure the A3 thinking approach supports knowledge-driven design, several learning cycles are identified and explained in the following section. The intention is to investigate how the knowledge created should be involved as part of the continuous learning cycle, and how efficient the current learning cycles are in encouraging the problem solvers to interpret and represent the created knowledge after having solved a design problem.

3.3 Learning Cycle for Product Design

The learning cycle is the continuous and overlapping process which leads to improved performance, process improvement and problem solving. One of the important aspects of the learning cycle is the creation of knowledge. This knowledge is created, captured and shared in different forms such as lessons learned, idea generation and decision making. The aim of the A3 thinking approach proposed in Section 1 is to support the knowledge-driven design stemming from efficient problem solving approaches and the appropriate learning cycle will provide a knowledge-rich environment. The authors have selected two learning cycles: a continuous improvement cycle (Plan-Do-Check-Act) and a knowledge creation cycle (Look-Ask-Model-Discuss-Act) that have already been applied in product development or manufacturing on the shop-floor [38,39]. The PDCA learning cycle is also represented in the traditional A3 report. However, based on its terminologies, the LAMDA learning cycle is a more straightforward approach and easier to understand than the PDCA. Despite the short title of PDCA, people sometimes misunderstand the implications and requirements of ‘Do’ and ‘Act’ in the acronym [40]. Therefore, the LAMDA learning cycle developed by Ward [41] has been chosen as the appropriate one for the A3 thinking approach and describes the process as follows:

- Look – Involve activities such as communication, observation and investigation to determine the best and most useful information and possible knowledge. The most important factor is to go and observe the problem area.
- Ask – Apply technique (e.g. 5 Whys) until the maximum amount of information is gleaned which will significantly influence how to solve the problem.
- Model –Model the simple ideas to help articulate thinking in order to visualise the knowledge based on the information from the look and ask steps.

- Discuss – Discussions to be held between the people involved to brainstorm the model/design and refine the ideas for implementation.
- Act – After the final decision has been made, the model is ready to act on and implement.

The following section provides an analysis of the limitations of the problem solving approaches that have been explained in sub-section 1. The focus is on identifying the processes utilised to solve a problem by considering the capability of knowledge creation, capture and sharing in order to support knowledge-driven design.

3.4 Limitations of the Problem Solving Approaches

The authors have defined the capability of knowledge creation for this work as: activities starting from visualising the essential process and information, to then addressing the problem. Knowledge is created through the activities of generating and implementing the solutions and measuring the results. During this activity, the learning cycle for knowledge creation, e.g. LAMDA[39], will guide designers to solve the problem and empower them to make decisions. Regarding the capability of knowledge capture, the authors have defined this as an activity in reflecting on the lessons which have been learned during and after solving a design problem. Meanwhile, the capability of knowledge sharing is an activity for creating and presenting useful knowledge gathered from the problem solving process in a simple manner. Therefore, 'useful knowledge' is defined as knowledge derived from a systematic process that enables designers to understand the linkage between hypothesis and practice which results in a new learning and understanding, hence formulating it into a design rule or design recommendation to be shared and communicated. All the above activities which are involved in knowledge creation, capture and sharing, hereafter are called the 'feature' as an aspect that needs to be considered in order to analyse the performance of the five problem solving approaches. Therefore, five features are defined as follows:

a) Visualise the necessary process and information to address the problem,
b) Present the generation and implementation of the solutions,
c) Provide the process of the learning cycle for knowledge creation,
d) Present reflections on the lessons learned, and

e) Create useful knowledge concisely from those actions, to be shared and communicated.

The limitations are developed based on the authors' understanding and by considering the capability of knowledge creation, capturing and sharing, as shown in Table 2in Section 4. From the table, the area colouredin grey, clearly shows that there is no approach which incorporates all the features; the following lists several conclusions made based on the limitations:

- All the problem solving approaches are covered in the first feature.
- Three approaches (A3, 8D and PAF) are covered in the second feature. However, the PAF approach does not fully present the generation and implementation of the solutions due to the PAF template visualising only the problem and correction but not the solution.
- The traditional A3 report performs at the third feature, which provides the PDCA learning cycle and is presented at the top of the A3 template. However, as seen from the reviewed learning cycles in sub-section 0.3.3, the PDCA is not the appropriate cycle for knowledge creation.

4 Knowledge-Driven Design Based on the A3 Thinking Approach

The analysis and limitations gathered from the problem solving approaches in Section 1, do not provide an appropriate solution for solving design problems. The reason for this could be that the knowledge created from the problem solving activities is not well-captured and documented. As a result, the company lacks knowledge sharing and produces more waste which then becomes a barrier to product development. Table 2 presents the A3 thinking approach aimed at addressing the summary of the limitations based on the five identified features explained in sub-section 3.4. The actions column ofTable 2shows short term actions based on the defined features. The idea is to encourage the designers to perform those actions by visualising the problem in order to create useful knowledge efficiently by using a new A3 template. The designers, who integrated all those actions from visualising to creating, are considered as having reached an appropriate solution, hence supporting knowledge-driven design. Kruger and Cross [41], in their study of the design process, define knowledge-driven design as being when a designer concentrates on using previous, structured, personal knowledge, and builds a solution on the foundation of this knowledge. However, in this paper we have defined that knowledge-driven design is the knowledge gathered from the integrated actions of visualising, solving, learning, reflecting and creating by using a new A3 template.

Table 2 Features and Comparison Approaches

<table>
<tr><th>Features</th><th colspan="5">Problem Solving Approaches</th><th></th><th>Actions</th></tr>
<tr><td>a) Visualise the necessary process and information to address the problem</td><td rowspan="3">A3</td><td rowspan="2">8D</td><td rowspan="2">PAF</td><td>RCA</td><td>5 Whys</td><td rowspan="5">A3 thinking approach <u>WILL</u> cover these features</td><td>Visualising</td></tr>
<tr><td>b) Present the generation and implementation of the solutions</td><td></td><td></td><td>Solving</td></tr>
<tr><td>c) Provide the process of the learning cycle for knowledge creation</td><td></td><td></td><td></td><td></td><td>Learning</td></tr>
<tr><td>d) Present the reflection from lessons learned</td><td></td><td></td><td></td><td></td><td></td><td>Reflecting</td></tr>
<tr><td>e) Create useful knowledge concisely from those actions to be shared and communicated.</td><td></td><td></td><td></td><td></td><td></td><td>Creating</td></tr>
</table>

Fig.1 illustrates a cycle of knowledge-driven design based on the integration of the aforementioned actions. Based on the research findings in Section 1, the authors have defined the A3 thinking approach as the one providing a new A3 template as a product design technique. Such a technique supports knowledge-driven design based on knowledge gathered from the integrated actions of visualising, solving, learning, reflecting and creating. The five actions shown in Fig.1 are further described, referring to the tools and outputs at each action in Table 2. Definitions of each action are explained as follows:

1. **Visualising –** this action will use a new A3 template provided from the A3 thinking approach to visualise the problem, solution and knowledge captured.
2. **Solving –** this action will solve the problem by following the elements provided by the A3 thinking approach sequentially structured and illustrated on a new A3 template.

3. **Learning –** this action, based on the LAMDA learning cycle, will guide its users on how to solve a design problem and to emphasize knowledge creation.
4. **Reflecting –** this action is based on the term 'reflection,' which means to support the problem solvers in turning their experience or understanding, both during and after solving the problems, into proper learning.
5. **Creating –** this action will use a new A3 report to represent the provision of the useful knowledge gained from the above actions to be shared and communicated.

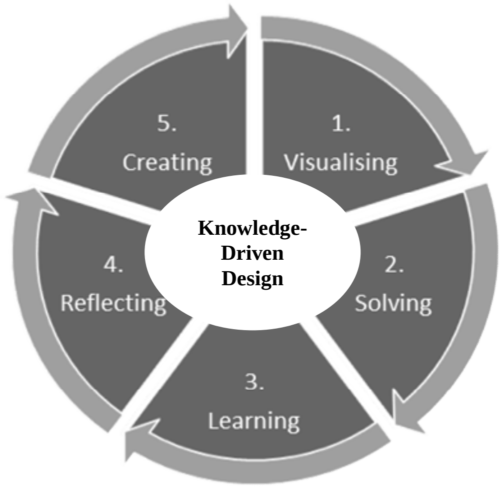

Fig.1 A Cycle of Knowledge-Driven Design

In brief, the knowledge-driven design based on the A3 thinking approach enables the designers to obtain a high level of understanding of the useful knowledge captured and documented in a new A3 report, which can be used as a reference or solution to eliminate design mistakes. This is to bridge the gap mentioned by Ward [39] that '*Almost all defective projects (projects that miss the market, have manufacturing cost or quality problems, or budget and time overruns) result from not having the right knowledge in the right place at the right time. Therefore, usable knowledge is the basic value created during product development. Usable knowledge prevents defects, excites customers, and creates a profitable operational value stream which is the goal of product development.*' The most important foundation of the A3 thinking approach is to develop a new A3 template, hereafter referred to as an A3LAMDA template, in order to differentiate it from the traditional A3 template. The A3LAMDA template consists of the elements emerging from the previous problem solving analysis performed in sub-section 1 that might effectively be used in product design. The A3LAMDA template, as shown in Fig.2, consists of two sections: Knowledge Creation and Knowledge Capture. The former was sequentially structured with the eight elements identified in sub-section 1 and the latter was provided with reflections based on questions; both are explained in more detail at the following sub-sections.

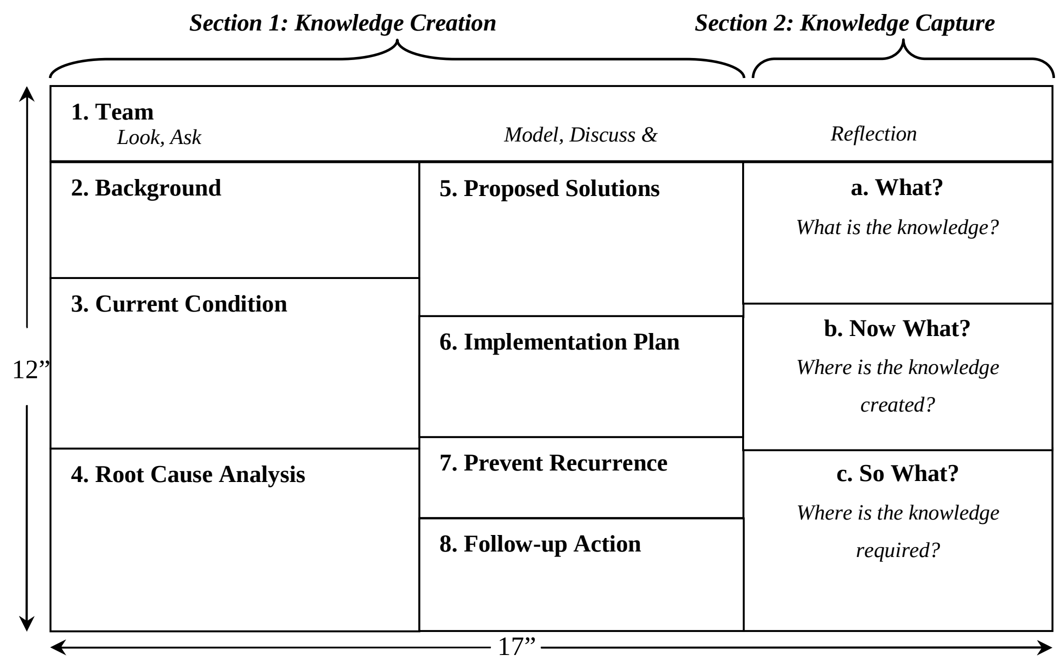

Fig.2 The New A3LAMDA Template

4.1 First Section: Knowledge Creation (Problem solving)

Knowledge in the A3 thinking approach is created through problem solving activity guided by the cycle of knowledge creation: LAMDA and utilising the A3LAMDA template. This template consists of eight elements, as shown in Fig.2, which were identified based on the phase-to-phase inter-relation analysis summarized in sub-section 1. The implementation for all the elements will be guided by the LAMDA learning cycle as a continuous improvement process. The first step in the A3 thinking approach will encourage the designers to perform the first (visualising), second (solving) and third (learning) actions in order to support knowledge-driven design. Visualising the necessary information and solving the problem using the LAMDA learning cycle will provide useful knowledge in order to offer effective decision making for the future project in a knowledge-rich environment. However, at this step, the designers are also encouraged to reflect on their actions and represent them on the right side in a reflection section, which is explained at the end of this section. The eight elements of the A3LAMDA template shown in Fig.2 are explained below, where each element is provided with a set of recommended topics that need to be considered in order to fulfil the purpose of each element:

1. **Team** – Build a team that involves a responsible person, report's author, date, title, and item/product.

   Proposed Tools: No tool is needed.

2. **Background** – Identify the details of the product or process, such as product type, name and code, software number, printed circuit board number, serial number, and customer specification. The A3LAMDA author can also add the goal of the problem solving or current state of the problem.

   Proposed Tools: Texts, bullet points, charts, graphs and sketches.

3. **Current Condition** – Identify the current condition based on 'Gemba' (from the Japanese for the place where work takes place) [42] then document and validate the observations very concisely and effectively to understand the real problem. The inputs of this element should be test request number, test type, functional status, performance class and occurrence. In addition, describe the effect of the failure, problem symptoms, clarify the fault description, attach and visualise the necessary data, confirm the design problem.

   Proposed Tools: Texts, tables, diagrams, graphs, sketches, tally sheets, current-state maps, histograms, scatter diagrams, flowcharts and check sheets.

4. **Root Cause Analysis** – Consider the most useful techniques to identify/explain the root cause for the current state visually. Diagnose the problem and identify types of design and the defect. Review all the analysis and discuss the results by sequentially listing the underlying causes of the problem. All these activities will discover the potential root causes. Explain the reasons for each cause.

Proposed Tools: Brainstorming, tree diagram, 5 whys, failure modes and effect analysis (FMEA), flowcharts, causal chains, tables, Pareto charts, scatter diagrams, problem assignment, problem impact matrix, cause and effect fishbone diagram, histograms, charts, weighted volume, relation diagram, sketches and graphs.

5. **Proposed solutions** – Explore a set of potential solutions that directly address the root causes. Apply the solutions and compare their effectiveness and confirm either that they are long term or containment solutions. Make sure the solutions address the root cause of the problem.

   Proposed Tools: Design reference, process flow, diagrams, sketches, graphs, charts, evaluation matrix, brainstorming, weighted volume, the evaluation and review technique (PERT) charts and theory of inventive problem solving (TRIZ).

6. **Implementation Plan** – Implement the corrective actions by highlighting the main actions and outcome, sequence, resources and support required, persons, and deadlines; also control and monitor the potential effect.

   Proposed Tools: Gantt chart (to display actions, steps, outcomes, timelines, and roles), tables, flowcharts, run charts and control plan.

7. **Prevent Recurrence** – Prevent product design problem recurrence by a) identifying the solution that could impact on other product and process designs, and b) discovering any consequences that possible solutions may cause to other products and processes.

   Proposed Tools: Provide right knowledge from previous design solutions and failure mode and effect analysis (FMEA).

8. **Follow-up Action** – Look at similar processes that can benefit from the countermeasure, be aware of any changes required for the improvement, measure the success of the implementation/improvement which includes realistic and quantified predictions based on an in-depth understanding of the work. Report closure for the successful corrective actions taken and reward the teamwork and efforts made.

   Proposed Tools: sketches, charts, graphs and tables, brainstorming and PERT chart.

The designer will use the LAMDA learning cycle as a guideline to solve any problems in product design. However, sometimes the designers do not recognise this created knowledge from the activity of problem solving. Therefore, in order to support the designers in capturing the created knowledge and transforming it into an A3LAMDA template, the authors have proposed the use of the 'reflection' practice. Turning a solution into learning, also called reflection, has been commonly used in education and is defined in different ways as follows:

a) *'Reflection is vital in any learning process; Reflection can help designers to learn from their experiences, help to become more conscious about the performed activities, learn which activities were not successful for reaching the design goal, and the actions that influence the design activities'* [43].

b) *'As designers learn lessons that enable them to construct designs, their lessons are reflected in the design procedure, problem analysis, and design solution'* [44].

c) *'The reflection is the process of stepping back from an experience to ponder, carefully and persistently, its meaning to the self through the development of inferences; learning is the creation of meaning from the past or current events that serves as a guide for future behaviour. One of the techniques for increasing the learning power of the reflection is the posing and answering of questions'* [45].

The authors have defined two categories of reflection: first, reflection in action (RIA), which means to reflect while the practitioners are solving the problem, and second, reflection on action (ROA) which is concerned with reflection after the problem has occurred [46]. This paper focuses on the latter, and the purposes of this type of reflection are:

- To identify the solution possibility during the initial steps.
- To enhance and support the understanding of the problem solvers in turning their experience of problem solving into proper learning after solving the problem.
- To develop the ability and confidence to criticise the initial understanding of a problem; hence construct a new description.

4.2 Second Section: Knowledge Capture and Sharing

Solving problems creates knowledge and this needs to be captured and shared to support decision making in future projects which then aids preventing problem recurrence. Knowledge capture is an activity performed in reflecting on the verified solutions or lessons which have been learned during and after solving a design problem. This activity takes place in the reflection section of the A3LAMDA template shown in Fig.2. In order that designers can capture the created knowledge, the Borton's reflection practice [47] based on the questions "what?, so what?and now what?" has been adopted in the reflection section and structured at the right side of the template. In this proposed new A3 thinking approach, designers could capture knowledge in the form of either design rules or design recommendations to be shared and re-used with other projects in a simple manner. The following present the reflection section:

a. What? – What is the knowledge?

   Knowledge is created through learning in the design problem solving process. This knowledge needs to be captured and documented as design rules or design recommendations. The design rule is defined as an important reference that is highly recommended when considering decision making for the future project whilst the design recommendation is defined as a general advice or suggestion based on the designers' experience of solving the problem. This is done by using a structured table (see Table 3), within the reflection section of the A3LAMDA, which consists of two main columns: a) design rules/design recommendations and b) design issues. The problem solving team will link the design rule or recommendation to the design issues.

Table 3 First element of the Reflection Section of the A3LAMDA Template: "What is the knowledge?"

		b) Design Issues				
a) Design Rule (DR)/ Recommendation (Rec)		Design Issue 1	Design Issue 2	Design Issue 3	Design Issue 4	Design Issue 5
DR 1	Rec 1					
DR 2	Rec 2					

b. So what? – Where is the knowledge created?

   In the design problem solving activities, knowledge is created after the proposed solution is implemented and the result verified. This is important in order to understand the origin of created knowledge and gives confidence for knowledge re-use in future projects.

c. Now what? – Where is the knowledge required?

   The designers need to identify which activities in the product development are where the design rules or design recommendations, captured in Table 3, will be needed. The idea is to provide useful knowledge for the right people and in the right place.

The following section presents a detailed case study from the automotive sector to demonstrate the A3LAMDA template, and hence to validate the A3 thinking approach.

5 Industrial Application of the A3 Thinking Approach

Today, the electromagnetic spectrum is widely used in electronic systems devices and has become the most important requirement in the automotive systems vehicle [48]. One of the main design challenges is the Electromagnetic Compatibility (EMC). The EMC is the ability of a device to control and prevent interference, or Electromagnetic Interference (EMI). EMI is a serious form of environmental pollution which causes malfunctions of electrical or electronic products [49]. This large scale system faces challenges driven by cost and designs that overwhelm the complexity of the system level EMC design [50]. Typical EMC design challenges include unpredictable EMC test results, a lack ofwell-established design rules, relatively new engineering disciplines, a lack of well-established EMC simulation software tools for the entire test spectrum, and dependence on multi-functional aspects such as electrical, software and mechanical systems. In order to address these EMC design challenges, it is important to develop a common understanding of the EMC design issue throughout the development process. Fig.3 shows an example of an electrical product workflow diagram. The case of a product failing the test means there is a design problem that must be solved by the designer. This means that the design is has to be modified and new prototypes made followed by re-testing. Such design iterations are costly and time consuming. The recurrence of the EMC design problems could be minimised by capturing and re-using the knowledge created as a result of solving the problem.

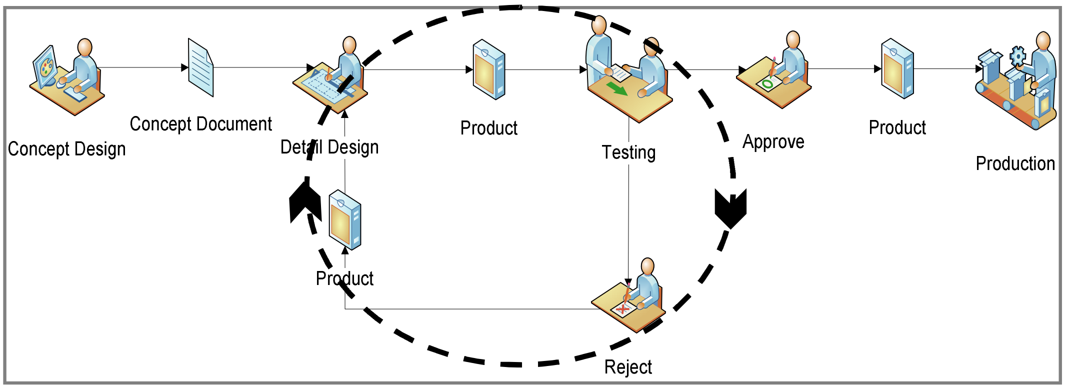

Fig.3 As-Is Workflow Diagram of the Product Development Process

For the purposes of this research, a case study has been selected from Visteon Engineering Services (VES) – a first tier supplier for major automotive Original Equipment Manufacturers (OEMs). Currently the company has several practices to document the different EMC issues. These have shown only limited success in preventing the recurrence of design problems. Therefore, there is a need for an integrated approach to document the failure, solve the design problem, capture and re-use the knowledge. The A3LAMDA, proposed in Section 4, has been used for this purpose to achieve the following goals:

1. Setting up a process to capture and provide EMC knowledge throughout the product development process.
2. Defining and designing standard templates (Failure documentation, Pass-Test knowledge, A3 and SMART checklist).
3. Implementing the A3 thinking approach to solve the design problem.
4. Capturing the link (inter-relation) between the templates to provide knowledge provision.
5. Knowledge provision;
    a. To solve the design problem under consideration
    b. To provide knowledge to new projects via the SMART Checklist

This paper focuses on point 3 above i.e.using the A3 thinking approach to solve the design problem by using an A3LAMDA template. Fig.4 shows the proposed To-Be workflow of an improved product workflow diagram.

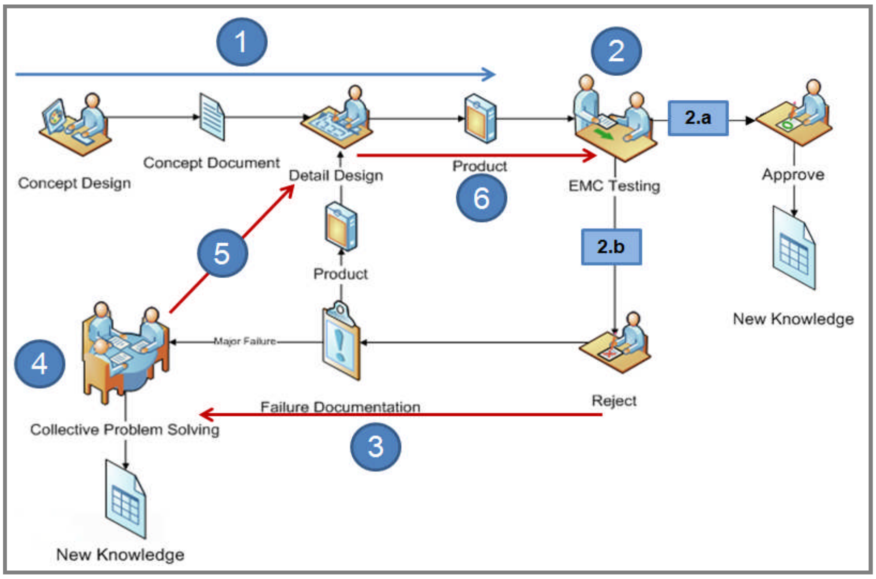

Fig.4 To-Be Workflow Diagram for Product Development Process

The following presents a description of each To-Be workflow activity.

Activity 1: The process starts with concept and detail designs of typical VES products, such as instruments cluster or audio. Several physical prototypes are produced for EMC testing to validate the final design.

Activity 2: During EMC testing there are two possibilities: a) pass or b) fail.

a. Products that pass the test are going to be documented in order to know in future which design configurations are likely to pass the EMC test. This is outside the scope of this case study.

b. Products that fail the test go back to detail design for re-work and undergo the A3 thinking approach to solve the design problem.

Activity 3: Problem solving starts with the failure documentation where the test engineers document the failure modes.

Activity 4: Problem solving is undertaken as a team exercise using the A3 thinking approach by using the A3LAMDA template as shown in Fig.2.

Activity 5: Once a solution to a problem is found the product is modified by detail design.

<u>Activity 6:</u>The modified product is then re-tested. If the part passes the test it means that the solution is verified and new knowledge is created. If the part fails the test the process is repeated from activity 3 until a solution is found.

5.1 EMC Failure Documentation

The A3 thinking approach has been applied to the collective problem solving, as shown in Fig.4 at activity 4, where the documented EMC design failure has to be solved. Most of the VES failure reports are done individually with different formats, and are not shared particularly well across relevant company functions. This lack of knowledge sharing contributes to the complexity of searching for the practical solutions that have been developed for particular EMC failures in the past. Therefore, a standard EMC failure documentation template is required and this is shown in Table 4.The template shown in Table 4 is based on a failure modes and effect analysis (FMEA) template, which includes the following key elements: a) function, b) failure mode, c) effect of failure, and d) risk priority number.

Table 4 Failure Documentation Template for EMC

<table>
<tr><th colspan="6">Failure Documentation Template</th></tr>
<tr><th colspan="6">Title:</th></tr>
<tr><th colspan="2">Function</th><th colspan="2">Failure Mode</th><th colspan="2">Risk Priority Number</th></tr>
<tr><td>Product Type</td><td></td><td>Test Type</td><td></td><td>Functional Status (Immunity</td><td></td></tr>
<tr><td>Product Name</td><td></td><td>Customer Spec.</td><td></td><td>Functional Performance Class (Immunity only)</td><td></td></tr>
<tr><td>Product Code</td><td></td><td>Test Request No.</td><td></td><td>Occurrence</td><td></td></tr>
<tr><td>Software</td><td></td><td rowspan="3">Other Information</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>Serial. No.</td><td></td></tr>
<tr><td>Printed Circuit Board No.</td><td></td></tr>
<tr><td colspan="6">Description of failure</td></tr>
</table>

The developed template is based on a modified version of the FMEA template; new sub-elements have been added to customise the template to the EMC needs and these are as follows:

a) Function: Product Type, Name & Code, Software, Serial and Printed Circuit Board (PCB) No.

b) Failure Mode: Test Type, Customer Specification, Test Request No., and other information.
c) Risk Priority Number: Functional Status, Functional Performance Class and Occurrence where each of the parameters is according to a customer's specification.
d) Description of failure: will describe observations during EMC Test or as a singledescription.

The following sub-sections present a case study to solve the EMC design problem by using the A3 thinking approach in the collaborating company. The product is called an "XCAR cluster" which failed the EMC test for radiated emission (RE). The RE is related to the radio frequency energy that is transmitted through a medium as an electromagnetic field [51]. The case study is used to demonstrate the implementation of the A3 thinking approach by utilising both templates, i.e. Failure Documentation and A3LAMDA.

5.2 Case Study of the A3 Thinking Approach in Capturing EMC Knowledge

The evaluation process of the newly presented A3 thinking approach started by presenting and guiding the application of the process and A3LAMDA template to engineers in order to start solving the EMC design problems. For this case study, three engineers were involved to form the A3 Team. The details of the case study based on activities shown in Fig.4 are presented as follow;

<u>Activity 1: Detail design for XCAR Cluster:</u> The XCAR is an instrument cluster that contains various gauges and indicators which the driver depends on to learn important information about the current status of the car. Gauges provide the information regarding speed, distance, heat and fuel. Indicator lights provide warnings and updates, such as the check engine light and the low fuel light. Different vehicles have different warnings available. In order to validate the XCAR design, several physical prototypes are made to undergo several mechanical and EMC tests. The latter is the focus of this research.

Activity 2: EMC Test for XCAR Cluster: The XCAR cluster failed the RE test which is radiated at 31.4MHz and this failure was identified by the EMC Test Engineer.

Activity 3: Failure Documentation: The EMC test failure is documented by the EMC Test Engineer, as shown in Table 5. This document is passed to the EMC Application Engineer to solve the RE issue with the current design of the XCAR cluster using the A3 thinking approach presented in Section 4.

Table 5 Failure Documentation Report for XCAR Cluster

Failure Documentation Template					
Title: Radiated Emission (RE) Test					
Function		**Failure Mode**		**Risk priority Number**	
Product Type	Cluster	Test Type	(REs)	Functional Status (For Immunity only)	A
Product Name	Cluster Class D-_01	Customer Spec.	XXX.01	Functional Performance Class (For Immunity only)	1
Product Code	XX-002-NBD	Test Request No.	TR.ER001XX	Occurrence	1
Software Number	12-34-56	Other Information	No		
Serial. No. (S/N)	XXXXX001-01				
Printed Circuit Board	XXXXXNBDS01				
Description of failure: The XCAR Cluster failed the RE test which is radiated at 31.4MHz.					

Activity 4: Collective Problem-solving using A3 thinking approach: In order to start problem-solving from the documented failure, the A3LAMDA template is used at this stage by the EMC Application Engineer, who is also called the A3's author. Appendix 1 shows the A3LAMDA report of the radiated emission issue of the XCAR cluster. The A3's author is required to fill in the basic data, such as team, date and the name of the report, in the 'Team' element. To ensure the speedy and accurate process of solving the problem, the inter-relation between the elements of Failure Documentationand A3LAMDAreports have been captured. In this case, the data of 'Background' and 'Current Condition' elements, as shown in Appendix 1, have been taken directly from the Failure Documentation report shown in Table 5.The 'Root-Cause Analysis' is performed as a group activity which consists of the EMC Test Engineer, A3's author (EMC Application Engineer) and individuals who were considered experts in EMC problem solving.

This activity started by putting the XCAR cluster in both daylight operating mode and night time operating mode in order to identify the possible cause of the design problem. Initial results showed that when the XCAR cluster was put in daylight operating mode, all the emissions disappeared. Such a preliminary observation could not be considered as a root cause of the problem until the diagnoses had been finished. Table 6 shows all the results from the diagnoses, where the constant current drive for the gauge illumination was the source of the emissions. From the group discussion, the emissions from the gauge illumination were caused by 'capacitor-X' that was incorrectly positioned on the PCB layout. This result had to be documented at the root cause analysis element in the A3LAMDA template, as shown in Appendix 1.

Table 6 State of Illumination for Daylight and Night time operating Mode

Diagnoses	Daylight Operating Mode	Night Time Operating Mode
Gauge illumination	OFF	ON
Backlight illumination	ON	ON
Pointer illumination	ON	ON

The 'Proposed Solutions'element in the A3 template is provided as a table that consists of a solution statement, confirmation (not effective, somehow effective and very effective) and types of solutions (containment and permanent). This is the start of knowledge creation. The solution is proposed and generated as a group decision, where capacitor-X needs to be placed close to the constant current drive circuit between the base and the collector of the voltage clamping transistor. The 'Implementation Plan' for the XCAR cluster was gathered from the discussion between the EMC Test Engineer and EMC Application Engineers (See Appendix 1).

<u>Activity 5: XCAR Cluster Design Modification:</u> The design of the PCB layout is modified by the EMC electrical engineering. The physical prototypes have been modified manually at the lab to place the capacitor-X close to the constant current drive circuit and between the base and collector of the voltage clamping transistor.

<u>Activity 6: Re-testing:</u> The modified prototypes undergo the EMC re-test and this time pass the test, i.e. there is no energy emitted. Hence, the proposed solution is

verified and new knowledge is created which is captured in the form of one design rule and one design recommendation in the following sub-section.

5.3 The Reflection of the Created EMC Knowledge

Sub-section 0.5.2 presented in detail the activities proposed in Fig.4. An extra step is then required to capture the newly created knowledge that resulted from solving the design problem of the radiated immunity of the XCAR Cluster. This is done by filling in two elements of the A3LAMDA report, which are 'Prevent Recurrence' and 'Follow-up Action', as shown in Appendix 1. Also the reflection section needs to be completed in order to transfer the experience gained into proper learning. In the case study the content of the 'Prevent Recurrence' element is as follows:

- Awareness: The constant current drive circuit will possibly go into positive feedback and so a capacitor-X is required to slow the response of the voltage clamping transistor to the pulse-width modulation (PWM) signal input on the base.
- Standardisation: On any constant current drive, the circuit should be packaged to protect a capacitor-X close to the clamping to stop the positive feedback. This should be captured in both the schematic and the layout document.

The follow-up action is to simulate the circuit in order to analyse the phase and gain margin to ensure the circuit is stable. After solving the radiated emissions failure for the XCAR cluster, the Borton's reflection model is implemented to reflect on the problem solving experience. This model consists of three different questions (What - So What - Now what) that enable the designer to reflect on their experience. The questions were answered as follows:

- **What** (What is the knowledge?): Formulate the solution or experience as a design rule or a recommendation.
  - Design Rule (DR1): Placing capacitor-X correctly in the printed circuit board (PCB) layout will prevent radiated immunity (RE).
  - Recommendation (Rec2): Implement the constant current drive circuit to ensure that the illumination is stable.
- **So What** (Where is the knowledge created?)

- The placing of the capacitor-X close to the clamping transistor to stop the positive feedback should be captured in both the schematic and the layout document.

- **Now What** (Where is the knowledge needed?)

DR / Red	Function	Activity
DR 1	Electrical Engineering	Schematic Design and Approval
Rec 2	Electrical Engineering	Create Electrical Bill Of Material

5.4 EMC Knowledge-Driven Design

This sub-section presents an argument based on the described case study of how the proposed A3 thinking approach contributes to the creation of a knowledge-driven design environment. This is conducted by addressing the five features listed previously in Table 2 as follows:

a) **Visualising the necessary process and information to address the problem –** Documenting the XCAR cluster that failed the RE test withagood level of detail and then integrating this data into the A3LAMDA template helped to visualise the process and the information necessary to start solving the problem.

b) **Presenting the generation of the solutions –** The A3LAMDA report has been effective in presenting the information and data after performing all the processes of the XCAR cluster problem solving that has led to the generation of the practical solution. Moreover, this report provides confirmation of the solution that the authors also considered for the knowledge that could be created, even if the solution were to fail. This is conducted using different types of data such as text using a recommendation style, and illustrative diagram or even computer-aided design (CAD) illustrations. This is also adding value to the visualisation of the solution.

c) **Providing the process of the learning cycle for knowledge creation –** The new A3 template is based on the LAMDA learning cycle. Such a cycle guided the A3 team to enhance knowledge creation and continuous improvement by solving the problem to create a knowledge-rich environment.

d) **Presenting the reflection on the lessons learned –** Presenting the reflection on action had three advantages. First, it helped the A3 team to verbalise their understandings or lessons learned during or after solving the problem. Second, it helped in formulating new understandings and lessons into a design rule or recommendation as useful knowledge. Finally, it helped in identifying where the useful knowledge is created and needed. This is to ensure the useful knowledge can be distributed and shared with the right person, in the right place and at the right time.

e) **Creating useful knowledge concisely from those actions to be shared and communicated –** The useful knowledge from the A3LAMDA report will be captured and provided as a design checklist or principles**.** The latter will be a standard set of structured questions to prevent the recurrence of similar failures and to help the designers to adopt the expected EMC test results.

6 Conclusion

The reviewed literature indicated that there are several problem-solving approaches used within the industry, some of which have also been used in support product design. However, they lack the provision of knowledge-driven design to ensure the enhancing of the quality of decision making through the development process. The authors identified three main challenges that hinder the full utilisation of the created knowledge. Therefore, there is a need to have an approach that is capable of knowledge creation, capture and sharing in order to reach the optimum product design solution. The features of an effective problem-solving approach are: visualise the necessary process and information, present the generated solutions, provide learning cycle process, allocate space for reflection from the lessons learned, and create useful knowledge to be shared and communicated. This paper has presented a novel A3 thinking approach to problem solving in product design. It also addressed the mechanism required to capture the created useful knowledge and provided a simple template to support communication and share knowledge. This approach provided a new version of the A3 template called A3LAMDA which incorporates new elements in order to address the features and provide a knowledge-driven design environment. In addition, the template represents the reflection in order to turn the experience of solving the design problem into proper learning. This approach has been successfully validated by demonstrating the use of the A3LAMDA report in an EMC design case study of an automotive electrical sub-assembly product cluster. Future work will focus on managing the A3LAMDA reports and the effectiveness of generating questions and rules for EMC design checklists, as well as managing the provision of knowledge to new projects. For example, developing the A3LAMDA template intoa computer system software could be advanced.

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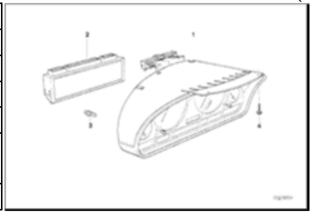
1. Team : AK, KS, & MS | Author: AK | Date: 22/10/1010 | Title: Radiated Emission (RE) Test | A3 Report No.:1234567890

Look, Ask | *Model, Discuss & Act* | *Reflection*

2. Background *(Look)*

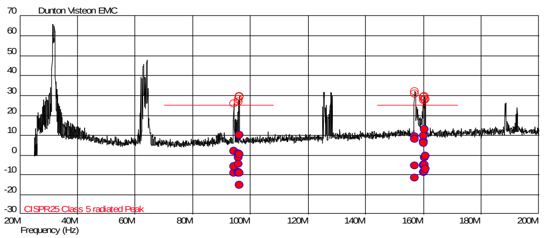
Product Type	Cluster
Product Name	Cluster Class D_01
Product Code	XX-002-NBD
Software No.	12-34-56
Serial No. (S/N)	XXXXX001-01
Printed Circuit Board No.	XXXXXNBDS01
Customer Spec.	XXX.01



3. Current Condition *(Look-Ask)*

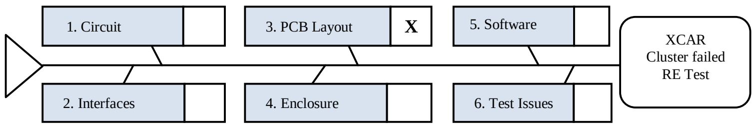
Test Request No.	TR.ER001XX	**Functional Status**	A
Test Type.	Radiated Emissions (RE)	**Functional Performance Class**	1
Other Information	No	**Occurrence**	1

Effect of Failure: The constant current drive circuit for the gauge illumination going into positive feedback and radiated at 31.4MHz.



4. Root Cause Analysis *(Ask)*

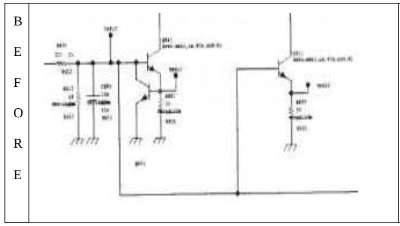
Any Diagnosis: - Putting the cluster in Daylight and Night time modes.

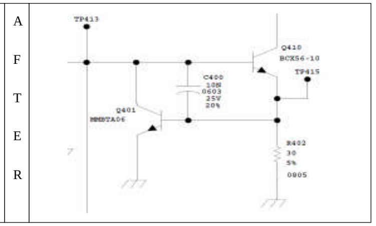


No.	Causes	Reason
3	Gauge illumination	-Daylight operating mode = OFF, Night time operating mode = ON.
		-Capacitor-X was incorrectly positioned in PCB layout.

5. Proposed Solutions *(Model-Discuss)*

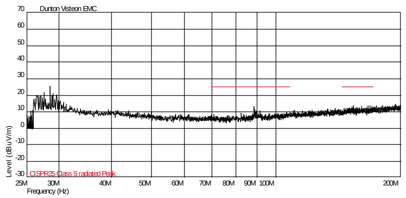
No	Solutions	Confirmation			Types of Solutions	
		N/EFF	S/EFF	V/ EFF	TMP	PERM
3	Put the capacitor-X close to the constant current drive circuit and between the base and collector of voltage clamping transistor.		x			x





6. Implementation Plan *(Discuss-Act)*

No.	Tasks	Actions to Implement Proposed Solutions	Responsibility & Duration
3.1	Redesign	-Put capacitor-X close to constant current driven circuit and between the base and collector of voltage clamping transistor.	Detail EMC Designer (1 Week)
3.2	Re-test	-The modified design for XCAR cluster performs the RE test.	EMC Test Eng. (2 weeks)



Result: The modified XCAR design cluster is Passed

7. Prevent Recurrence *(Act)*

-**Awareness**: the constant current drive circuit will possibly go into positive feedbacks and so a capacitor -X is required to slow the response of the voltage clamping transistor to the PWM signal input on the base.

-**Standardisation:**On any constant current drive circuit it should package protect for a capacitor-X close the clamping to stop the positive feedback should be captured in the schematic and the layout document.

8. Follow-Up Action *(Act)*

- **Continuous improvement:**Simulation of the circuit to analyse the phase and gain margin to ensure the circuit is stable.

a. What?

What is the knowledge?

- Formulate the Solution OR Experience as Design Rule (DR)/Recommendation (Rec):

Design Rules (DR)	Design Issues: Circuit Design	PCB Layout	Interfaces	Software	Enclosure Design	Other
DR 1 Rec 1 Placing the capacitor-X correctly in PCB layout will prevent radiated emission.	X	X				
DR 2 **Rec 2** Implement the constant current drive circuit to ensure the illumination is stable.		X				
DR 3 Rec 3						

b. So What?

Where is the knowledge created?

- The placing of the capacitor-X close to the clamping transistor to stop the positive feedback should be captured in the schematic and the layout document.

c. Now What?

Where is the knowledge needed?

DR / Red	Function	Activity
DR 1	Elec. Eng.	Schematic Design and Approval
Rec 2	Elec. Eng.	Create Electrical Bill Of Material

Appendix 1: A3LAMDA Report for Cluster Class D_01 Failed Radiated Emissions Test