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A Systems Approach to the Development of Enhanced Learning for Engineering Systems Design Analysis

Ed Henshall[a], Felician Campean[a]* & Brian Rutter[b]

[a]*University of Bradford, UK*
[b]*Ford Motor Company, UK*

* Corresponding author. Tel.: +44-127-423-4569 . *E-mail address:* F.Campean@Bradford.ac.uk

Abstract

This paper considers the importance of applying sound instructional systems design to the development of a learning intervention aimed at developing skills for the effective deployment of an enhanced methodology for engineering systems design analysis within a Product Development context. The leading features of the learning intervention are summarised including the content and design of a training course for senior engineering management which is central to the intervention. The importance of promoting behavioural change by fostering meaningful learning as a collaborative process is discussed. Comparison is made between the instructional design of the corporate learning intervention being developed and the systems engineering based product design process which is the subject of the intervention.

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Keywords: Failure Mode Avoidance: Learning Intervention; Systems Engineering, Social Constructivist Learning, Taxonomy, Learning Objectives.

1. Introduction

The highly competitive nature of the automotive industry with the rapid advancement of new technologies such as those associated with semi-autonomous and autonomous vehicles and ever more stringent ecological constraints results in a need to continuously upskill the product design community. The increasing complexity and ubiquitous multidisciplinary nature of systems requires evolution of design theories and methodologies (DTM). This is particularly needed to support functional integration across the different disciplinary domains with a sharp focus on handling increasingly complex requirements throughout the system's lifecycle [1]. For DTM methodologies to be effective in driving change in industry, the development of skills necessary for their effective utilisation is a key enabler. However, development and practical deployment of effective learning interventions for DTM skills is notoriously challenging: the perceived demand for fast pace new product development and introduction does not immediately provide an environment for testing, validation and adoption of enhanced, more rigorous methodologies.

This paper reflects on the experience of developing a corporate learning intervention aimed at developing skills for enhanced methodology for engineering systems design analysis and its effective deployment within a Product Development context of an automotive OEM. The requirement for enhanced design practices, underpinned by updated knowledge and skills, was pragmatically driven by the need to enhance the efficiency of Product Development, in particular to address the volume of design rework, substantiated by the large number of engineering changes made late in the design process, resulting in difficulties in meeting launch timing and inevitable cost increase. While Failure Mode Avoidance (FMA) [2] methods and tools focused on early identification of design failure modes had been introduced in the Company's design process for a long time, these were not fully integrated with the product development process (PDP) [3]. Furthermore, the effectiveness of the FMA methods was found to diminish in the face of increased systems complexity and multi-disciplinarity. An enhancement of the FMA methodology was therefore required to address (i) the need for a stronger focus on the integration of early design failure avoidance analysis

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with the complex system requirements; (ii) the need for a more effective (coherent and comprehensive) information flow in the methodology, linking functional requirements with robust design analysis and design verification methods; (iii) the effective integration of the methodology with the stage-gate PDP operated by the company. The associated requirement for training was focused on developing both technical and interpersonal skills to enable the effective and efficient deployment of the methodology in the PDP practice.

The Failure Mode Avoidance framework developed by the University of Bradford Engineering Quality Improvement Centre (BEQIC), illustrated in Figure 1 [4], was employed to underpin the enhanced FMA methodology. The strength of the BEQIC FMA framework is that it incorporates methods and tools (such as Failure Modes and Effects Analysis, FMEA) already in use within the industry, which facilitates its adoption. The key innovations of the methodology derive from its focus on a structured approach to Function Analysis; this is underpinned by the introduction of a methodology to support coherent solution independent functional reasoning, as well as a detailed interface analysis method to characterise interactions at systems interfaces and systematically capture functional requirements for system integration [5]. This facilitates an effective approach to handling the complexity of systems design, in a context where an increased amount of new technology is introduced, thus requiring a top-down analysis for systems architecture development and integration. The function failure analysis, development of robust countermeasures and robust design verification phases of the BEQIC FMA framework are strongly driven by the function analysis methodology through coherent information flow linking the supporting methods and tools.

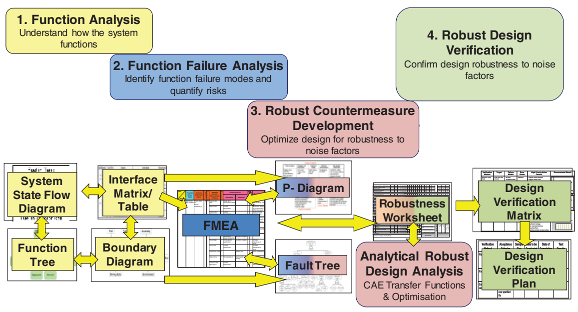

Figure 1: BEQIC FMA Framework

A customised version of this methodology was developed with Company experts experienced in extending the FMA process, and embedded into a framework referred to as SEED (Systems Engineering Excellence by Design) [6]. The effectiveness of the methodology was validated with a case study on a complex multidisciplinary automotive system (namely an exhaust aftertreatment system). An effective llearning intervention for SEED was required to support the effective deployment of the methodology within the organisation. It was recognised from the outset that the learning intervention must address both the engineering technical skills needed to implement the methodology for the engineering systems analysis and design, as well as the interpersonal skills that facilitate its effective deployment. It was also recognised that interpersonal skills play an essential role across the hierarchical levels within the PD organization. At all engineering levels, such skills are needed to facilitate the inter-disciplinary technical communication needed for system functional and structural architecting analysis, as well as ~~for~~ the adoption of revised methodologies based on methods that have been used for some time. At management levels, effective interpersonal skills are required to ensure the adherence of the methodology in the PDP, e.g. shifting to a process based paradigm in reviewing the integrity of deliverables at gateways.

This paper presents in detail the systematic instructional design approach adopted for the development of a set of learning interventions for the SEED design methodology. The instructional design framework is first considered, followed by analysis of learning requirements, and the design solution for the learning intervention. The paper ends with a reflection on the experience with the deployment of the learning intervention in the organisation.

2. Instructional Design Methodology/Theory

A key initial step in the design of a learning intervention is to establish a clear set of customer requirements expressed as learning objectives. Learning objectives define the expected behaviours exhibited by those who participate in the intervention i.e. describe what the learner must be able to do or perform [7] as a result of learning. Learning objectives associated with engineering will relate to tasks which range from the relatively trivial to the highly complex. To be effective, any learning intervention must give the learner the skills and knowledge to perform the complete range of tasks. To help ensure that this is the case it is useful to categorise learning objectives by degree of complexity/difficulty. A number of taxonomies of learning objectives are currently in use for such categorisation of which the most widely used are those due to Bloom [8], Biggs & Collins [9], Anderson & Krathwohl [10] and Fink [11].

Bloom's original taxonomy uses 6 hierarchical levels of cognitive learning ranging from the simplest to the most complex. Anderson & Krathwohl built upon Bloom's work with a revision to the higher learning categories and the addition of a knowledge dimension. The SOLO (Structure of Observed Learning Outcomes) developed by Biggs & Collins has 5 hierarchical levels of learning and differs from the Bloom and Anderson & Krathwohl taxonomies by being aimed at both educators and learners; this allows learners to see that their learning is due to their efforts and strategies. Fink's Taxonomy of Significant Learning has 6 interrelated major types of learning which include Human Dimension, Learning how to Learn, and Caring in addition to Foundation Knowledge and Application. Fink's taxonomy differs from the other taxonomies by being an integration of non-hierarchical dimensions.

While Fink's approach would seem to fit the SEED leaning intervention, which aims to include an element of interpersonal skills, an adaptation of the Anderson & Krathwohl taxonomy was ultimately preferred for two main reasons. Firstly, the client for which the leaning intervention was developed had a clear requirement for a classroom course with follow-up application support. Secondly, the authors' experience of designing technical learning in conjunction with learning stakeholders is that it is often more efficient if the instructional systems design methodology is largely transparent during the meetings of the learning intervention design team, as engineers often see the methodology as time consuming and non-value add. It was felt the Anderson & Krathwohl taxonomy leant itself to this type of transparency better than the Fink taxonomy.

The Anderson & Krathwohl taxonomy can be represented as the 3-Dimensional Map shown in Figure 2, which is adapted from the graphic due to Heer [12]. The Cognitive Process Domain and Knowledge Domain categories shown in Figure 2 are defined in Table 1 as they relate to the SEED learning intervention.

Table 1. Anderson and Krathwolh Taxonomy: Categories within Dimensions as they relate to the SEED Learning Intervention

Cognitive Process Dimension	Knowledge Dimension
Remember: Retrieve SEED knowledge from long-term memory	**Factual:** The foundations of SEED that must be known
Understand: Perceive meaning within SEED learning content	**Conceptual:** Interrelationships between SEED tools and elements
Apply: Use SEED methodologies within the SEED framework	**Procedural:** The work/ information flow within the SEED framework
Analyse: Determine how the SEED tools relate to each other and the overall framework	**Metacognitive:** Awareness of one's own cognition of SEED
Evaluate: Judge material based on SEED criteria	
Create: Design failure free product using SEED	

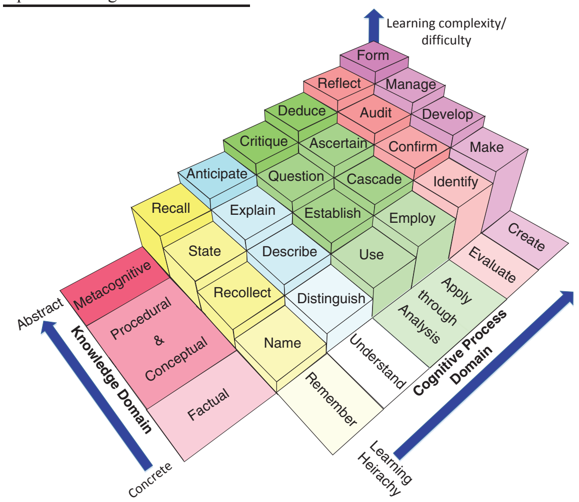

Figure 2: Three-Dimensional nature of Anderson and Krathwolh Taxonomy

Overall the learning complexity/difficulty increases diagonally across the 3-Dimensional Map from the Remember/Factual category to the Create/Metacognitive category. The Anderson and Krathwohl taxonomy separates the Cognitive Process categories of Apply and Analysis and the Knowledge types of Procedural and Conceptual. These categories have been combined in applying the taxonomy to SEED since the procedures in SEED are based on conceptual information flow and applied through analysis. It is recognised that the taxonomy should be used for guidance and as such overlap between learning objectives in adjacent categories may occur.

The taxonomy is cumulative in the sense that effective learning in the higher-level categories is dependent on previous learning in the lower level categories. The key implication of the taxonomy for the SEED learning intervention is that learning must be achieved in all categories. Such learning needs to be meaningful, i.e. it must provide the learner with the knowledge and cognitive processes they need in order to perform tasks that they have never completed before. The view of how meaningful learning is best achieved has changed over time from the perception that knowledge can be transferred from teacher to student (objectivist learning) to the idea that knowledge is created by a student interpreting what they hear and read based on previous learning (constructivist learning). Today there is a move towards achieving constructivist learning socially i.e. by individuals creating knowledge through interaction with others [13, 14].

It is recognized [15, 16] that the effectiveness of learning strategies varies with the level of learning that is required. For example, presentation/lecture based objectivist orientated learning is best suited to lower levels of learning, while social constructivist learning in small group activities lends itself to intermediate level of learning in a training environment. Workplace application is often the most effective environment for achieving the higher levels of learning.

3. Analysis of Learning Requirements

Following the establishment of learning requirements, it was concluded that both Engineers and Engineering Management required good knowledge and understanding of the SEED methodology, i.e. common lower level learning. The emphasis of learning at higher levels differs between the two groups with Engineers learning continuing to focus on the SEED methodology while that for Engineering Management being directed toward the control of the SEED methodology. Thus, while Engineers working within SEED teams are required to conduct, evaluate and create their own SEED analysis, Engineering Management need to scrutinize and assess the work of the engineering team. For example, Engineering Management should confirm that the engineering team are using SEED tools and methods in an appropriate manner and that the conclusions the team draw from their analysis are valid. This difference of role is reflected in different learning objectives for the two groups particularly at the higher levels of learning in the Conceptual and Procedural category, of the Knowledge Dimension. An example learning objective for each category of the taxonomy is shown in Figure 3. Many objectives in the higher levels of Factual and Metacognitive are common to both groups.

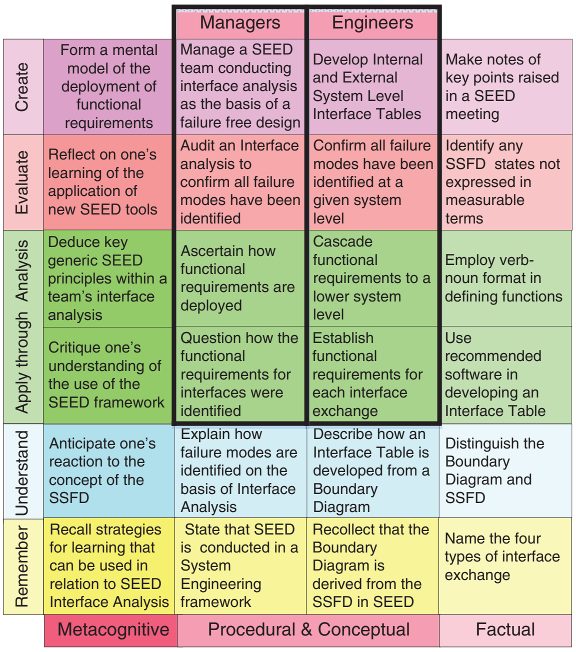

Figure 3. Example Learning objectives for SEED

Learning is enhanced when interaction is conducted within a constructive rather than interrogational environment. Enhanced interpersonal skills facilitate constructive interaction. In the context of SEED, interpersonal skills are a part of the broader concept of People Skills [17] which include skills relating to self-awareness. While not discussed in detail in this paper, interpersonal skills are seen as equally important as the technical skills they support.

In view of the highly educated and experienced nature of the audience, their previous exposure to FMA and the pressure on their time it was felt important that participants find the learning intervention to be motivational, enjoyable, interesting, challenging, value-add and of relative short duration. In addition, the learning needed to be applied in the highly complex context of automotive product design.

4. SEED Learning Intervention Design Solution

Following the analysis of the learning requirements, it was decided to design two distinct parts to the SEED learning intervention one focused on Engineering Management and the other on Engineers. The primary learning strategies adopted for the different levels of learning are shown in Table 2.

Table 2 The Primary Learning Strategies by Level of Learning.

Cognitive Process Dimension	Primary Learning Strategy			
	Training Course			Coached Application
	Presentation	Discussion	Activity	
Remember	•	•		
Understand	•	•		
Apply through Analysis		•	•	•
Evaluate		•	•	•
Create		•	•	•

The Engineering Management and Engineers training courses were designed as 2 and 4-day duration respectively. The intervention was deployed in the Company top-down, with Engineering Management attending the 2-day course prior to the launch of the Engineers training. Extended learning through coached application was incorporated into the post-course workplace activities on project based systems analysis and design. Due to the structural complexity of the courses, a team of two facilitators with expertise in both the methods and tools underpinning SEED as well as People Skills, was required for course delivery.

The main challenge in designing the SEED learning intervention was to ensure that meaningful higher level learning occurred through the course activities and coached application. To promote constructivist learning in the Training Courses a single coherent case study was used as central to the storyline for both the presentations and the activities. The case study was based on a real-world application reflecting the level of technical complexity inherent in automotive product design. Since the presentation material might otherwise tend to drift towards objectivist lower-level learning, the main training room for the courses was set up to facilitate social constructivist learning. Discussion between participants was encouraged by seating them in a horseshoe of chairs without tables so that they could all see one another as well as the facilitator and presentation screen. Both training courses were designed for two groups of 6 people in the activities with an audience of 12 corresponding to the upper limit for the plenary arrangement. The audience size was felt to be a reasonable trade-off between educational efficiency and corporate cost in an organisation were the potential global audience numbered in the thousands, recognising that most of the expenditure incurred in running training courses in a commercial organization is due to participant time away from the job.

The high-level design of both training courses was based on the SEED workflow and framework. with the courses divided into 4 principal sections corresponding to the systems engineering decomposition framework; see Table 3.

Table 3. Engineering Management Course High Level Design

Section	Content
1	System Level Analysis The Team System and Effective Meetings Activity: System Level Interface Analysis Design Review
2	Subsystem Level Analysis Communication Skills: Speaking and Descriptive Feedback Activity: Subsystem Level Interface Analysis Design Review
3	Component Level Analysis Attitudes, Questioning for Content Activity: Component Level Interface Analysis Design Review
4	Traceability and Verification The Virtual Team, Listening Activity: Verification through the Systems Hierarchy

Each day of the courses included Warm-up and Warm-down sessions with discussion related to the day's content. The principal sections were a blend of technical and People Skills presentation and small group activity. Overall, significantly more than half of the course duration was devoted to group interaction and activity. The People Skills were set the context of the Team System and chosen to enhance the activity that they were presented immediately prior to. Common material was used in the two courses, with the Engineers looking at the SEED methodology and tools in greater depth and at a more deliberate pace. Given the iterative nature of deployment of the SEED methodology through the systems hierarchy (shown in Table 3) participants were exposed to the methodology three times, helping to reinforce learning.

The first three Engineering Management course activities demonstrate the way in which higher level social constructivist learning was promoted in the context of a formal training course. Each activity comprised of two parts:

- Part 1: Two breakout groups were asked to review SEED analysis at the designated system level. One group were asked to act as the Engineers that had conducted the analysis, and to defend its integrity in a design review. The other group, the Engineering Management, were asked to assess the integrity of the analysis.
- Part 2: The groups met around a single table in a simulation of a Design Review meeting, with the Engineers presenting their analysis, and the Engineering Management reviewing and assessing this work.

Roles were rotated from one activity to the next enabling each participant to role play an Engineer and Engineering Management. The activities were associated with key PDP engineering deliverables related to the case study illustrated by those for the System Level activity in Table 4. Coherent information flow between activities within the SEED Systems Engineering framework reflected the case study's central role.

Table 4. Key System Level PDP Engineering Deliverables

Engineering Context	Key Engineering Deliverables
A proposal to introduce fuel directly into the exhaust to improve Diesel Particulate Filter regeneration, reduce oil dilution and so improve service intervals.	Key FMA related system level deliverables for the given Vehicle Program are: • A comprehensive list of the interfaces required for the successful integration of subsystems into the Powertrain • All system level function failure modes associated with both historical problems and the introduction of new technology are captured in the Powertrain DFMEA

To support the understanding of the technical background of the case study considered in part 1, participants were taken though the SEED analysis associated with achieving the PDP deliverables by a technical expert from the company who was a member of the course development team. This analysis focused on the information flow associated with the key deliverables within the corresponding Powertrain System State Flow Diagram, Boundary Diagram, Interface Tables and System DFMEA, and was aided by having large-scale versions of the documents on display, supporting evidence based technical discussions. In Part 2, the simulated engineering Design Review, the groups met around a table, with the large-scale documents available on display. The Engineers group were tasked with presenting the analysis "they had conducted" to achieve the PDP deliverables, with the Engineering Management reviewing and questioning this analysis. Both groups were given a set of questions typically asked in a System Level Design Review discussing the engineering actions taken to address an historical concern; Table 5.

Table 5. Typical Questions asked in a System Level Design Review

Typical System Level Design Review Questions
In relation to a historical customer concern: • What Powertrain level interfaces are associated with the concern? • What is the nature of the exchanges that occur at these interfaces? • How can you be sure that you have identified all significant interfaces? • What functional requirements are associated with each interface exchange? • What failure modes are associated with these interfaces at Powertrain level? • How can you be sure that you have captured all potential failure modes? • What Powertrain level functional requirements should be cascaded to the Exhaust Aftertreatment System?

Participants managed the simulated Design Review themselves using the Effective Meeting skills introduced in the preceding People Skills presentation. Occasional recourse to their technical expert was allowed. Assessing the answers to the above questions corresponds to the learning objectives stated in "*Apply through Analysis*" and "*Evaluate*" levels of learning in the Managers "*Procedural & Conceptual*" Knowledge dimension in Figure 3. Conducting the meeting satisfactorily relates to the "Create" objective.

The group was observed throughout part 2 of the activity by the course facilitators who provided Descriptive Feedback on the individual behaviours observed. Descriptive Feedback, a People Skills topic included in the course, is purely factual without judgement. Feedback on the technical accuracy of the discussion was also given. In a short Warm-down participants commented on how they felt about the activity.

Attention was also directed within the training courses to the development and application of metacognitive knowledge. For example, Engineering Management participants were asked in the day 2 Warm-up to reflect upon and discuss what they were going to do differently in Design Review meetings as a result of what they had learned the previous day.

It was decided to promote higher-level learning through workplace application using expert coaching of People Skills and Technical Skills to groups of engineers working on SEED projects and in Design Reviews. Coaching would also be available for Senior Engineering Management on both a one-to-one basis and in SEED related meetings. A number of experienced engineers were given extensive training, including in-depth SEED Technical and People Skills over and above those included in the training courses, to enable them to act as effective coaches and training facilitators.

5. Discussion and Conclusion

Implementing the SEED methodology in an automotive OEM necessitated the design and development of an effective learning intervention to address an important business need and minimise participant time away from the job.

The product development process requires engineers to exhibit behaviours corresponding to the highest levels of learning as a matter of course. Coherent with the systems engineering focus of SEED, the SEED learning intervention was designed using a systems approach. Clearly defined spoken and unspoken design requirements were crucial, with spoken requirements being expressed as learning objectives and the way people learn being an unspoken element. Defining learning objectives enabled the knowledge content of the learning intervention to be identified, and more importantly to specify how participants were expected to apply this knowledge. Categorising learning objectives in a taxonomy helped to ensure that the learning intervention covered all levels of cognitive learning and all aspects of knowledge, including metacognitive, with learning being promoted by a range of learning strategies and approaches.

The learning intervention was designed to align with the two different roles of Engineers and Engineering Management and to build upon their existing knowledge and experience. A significant element of social constructivist learning was included in the training courses through the design of small group activities in which participants were expected to exhibit behaviours associated with higher level learning centred on an engineering scenario with a technical content commensurate with what they experienced in the workplace. Team/People skills learning that directly facilitated technical aspects of SEED process application was included as an integral part of the learning intervention. Recognising that asking experienced participants to change the way in which they manage key aspects of the product design process with a new way set in an existing familiar context could sometimes be met with a level of resistance, the course was purposely designed to build on participant current knowledge and experience to encourage active participation. This was achieved by having meaningful constructivist learning within small group work and discussion as a dominant feature of the training courses and focusing higher level constructivist learning towards workplace application. The use of expert coaches in the workplace provided a powerful environment for social constructivist learning. Discussion between participants during the training courses was encouraged, for example, by paying attention to room furniture and information layout.

Polarising the complex process of learning as objectivist or constructivist is an oversimplification. Nevertheless, this model and others such as the categorisation of learning objectives into a taxonomy are very useful in designing a learning intervention. It is seen as important that instructional design methodologies are tailored to a particular application and used flexibly rather than being a series of tasks to be conducted for their own sake; i.e., like SEED, the conceptual thinking behind a methodology is as important as the methodology itself.

The design of the SEED learning intervention contrasts with the approach often seen in technical training design in an automotive and non-automotive industrial context. Often being predominantly based on a series of PowerPoint presentations or computer screens, with any activities based on a greatly simplified engineering scenario from that met in everyday activities, such courses are necessarily focused towards lower level objectivist learning. It is not surprising that full learning effectiveness is not achieved if participants are largely left without learning support when attempting to apply the knowledge they have gained in the workplace. Arguably, this is a plausible explanation why many design theories and methods have poor permeation into in engineering practice.

The SEED course has been deployed within the OEM on a global basis with significant numbers of managers and engineers participating. Feedback on the courses has been overwhelmingly positive. The ultimate measure of success of the SEED design methodology and learning intervention must reflect on the goal that instigated its development: right first time through design, with significantly reduced engineering changes. This evaluation will be the subject of a future study. Further work in the application of instructional design to vocational education and training would also be beneficial.

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