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Procedia CIRP 53 (2016) 166 – 172

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The 10th International Conference on Axiomatic Design, ICAD 2016

Application of Axiomatic Design for Project-Based Learning Methodology

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Abstract

Project-Based Learning is a method based on constructivist finding, its application is centred on project development as the learning tool catalysing knowledge discovery. Project-Based learning have been traditionally designed and implemented on a know-how and trial-and-error basis, but tasks and decisions taken during the design phases of the training modules have a substantial effect on its quality and outcomes. Axiomatic Design can contribute to improve the outcomes opportunities and the process efficiency by identifying where complexity exists within the requirements and design activities that underpin the model. In this study, the Axiomatic Design method is applied to link learning outcomes of Lean Six Sigma training with all the teaching processes and the availability of resources. As a conclusion some improvement suggestions are made to optimize the learning and teaching methodology in order to maximize the learner outcomes.

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Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design

Keywords: Axiomatic Design; Project-Based Learning; Lean Six Sigma; Training; Education

1. Introduction

Project-Based Learning is a constructivist pedagogy where learners use theoretical and technical knowledge to find solutions for practical problems. It is a learner-centered methodology involving a dynamic classroom approach in which learners acquire a deeper knowledge through an active exploration of real-world challenges and problems. Project-Based Learning changes the teachers' role from instructor to facilitator in order to develop the learners' technical proficiency as well as critical thinking, team collaboration and a set of attributes necessary to maximize problem solving. Project-Based learning (PBL) is a method of based on the constructivist finding allowing learners to gain a deeper understanding of the topics when they actively construct their understanding and competencies by working with and using ideas. In Project-Based learning, learners engage in real, meaningful problems similarly to what scientists, mathematicians, writers, and historians do when working through the research paradigm. Project-Based learning date back over a hundred years and can be attributed to the work of educator and philosopher John Dewey [1]. A Project-Based classroom allows learners to investigate questions, propose hypotheses and explanations, discuss their ideas, challenge the ideas of others, and try out new ideas. Learning environments that are Project-Based have five key features:

1. Start with a driving question and a problem to be solved.
2. Learners explore the driving question by participating in authentic inquiring processes of problem solving meaningful

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Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design
doi:10.1016/j.procir.2016.08.003

in the discipline. As learners explore the driving question they earn and apply functional and problem solving competences.

3. Learners and facilitators proceed through the class with collaborative activities to find solutions to the driving question(s). This mirrors the social complexity and enhance the 21st century skills in addition to the functional skills required by the disciple itself [2].

4. While engaged in the inquiry process, learners use abilities and technologies that help them participate in activities normally beyond their ability.

5. Learners create a set of tangible project/products that address the driving question. These are shared and represent the class's learning.

With particular regards to Continuous Improvement (CI) and Lean Six Sigma (LSS) [3], the most important value of such programs deployment is the development of competencies among the people, leading to both a deep knowledge of processes and a stimulus towards Operational Excellence as well as a motivation a sense of belonging to the organization [4] Competence is the combination of:

- *Knowledge* – the understanding about a specific subject, gained through education, training and experience;
- *Skill* – the ability to put a knowledge into practice, acquired through experience and practice;
- *Behaviour* – the "translation" of knowledge and skill into daily activities, that is the way of reacting to particular situations, obtained through experience.

Lean Six Sigma agents in particular need to be able to combine statistical and optimization tools knowledge with critical thinking, problem solving and people management skills which represents the functional characteristics to implement such type of CI. Key competencies can be resumed by the Competency Chart illustrated in Figure 1 where are reported the characteristics of the ideal Lean Six Sigma agent profile, indicating the initial, the required levels as well as the ones reached at the completion of the Project-Based Learning training module. By identifying the competency gaps it is possible to plan specific training programs by prioritizing competencies needed.

The most effective method to deploy LSS culture among a company is the *Learn-Do-Apply* approach, in which training sessions allow for Project-Based Learning in order to facilitate competencies acquisition, through the practical application of methodology and tools. Questions are the initial step of any class or design project, they represent the problem definition phase. Knowledge resides in the questions that can be asked and the answers that can be provided as indeed Aristotle suggests "the kinds of questions we ask are as many as the kinds of things which we know" [5].

LSS trainings start with questioning the participants with issues to address with LSS methodology, while through out the training process they are assisted in enhance and improve

Fig. 1. *Competency Chart* indicating progress of the competencies levels of a LSS agent

their performance through continuous feedbacks on how to apply a specific knowledge. Trainers support the learners though out the Design-Measure-Analyse-Improve-Control (DMAIC) roadmap by facilitating the proper tools knowledge acquisition and the respective application of them to the DMAIC methodology, working out any statistical issue [6] raised during the project execution [7]. To optimize the proposed methodology and to affect the training product quality and productivity, this study adopts systematic design model rather than the traditional ones based on know-how and trial-and-error. The systematic phases to develop a solution to increase efficiency of the training are facing the mental inertia and avoiding to show the possible solutions to be implemented. Axiomatic Design (AD) is used as the tool to design the LSS training model, while the Project-Based Learning (PBL) perspective training is used as the theme for the decomposition, starting from an overall perspective to then focus on training design [8]. Axiomatic Design indeed provides a framework in which the design process can be managed [9,10] and particularly, it provides criteria for distinguishing bad designs from good ones [8]. The systematic bi-dimensional decomposition used in Axiomatic Design facilitates the inclusion of all the relevant variables and scenarios, as well as contexts and situations. The first dimension of the decomposition into functional, physical, and process domains provides a clear categorization of Functional Requirements (FRs), Design Parameters (DPs), and Process Variables (PVs). These represent the domain where the concepts "WHAT we want to achieve" and "HOW we want to achieve it" lie (Figure 2).

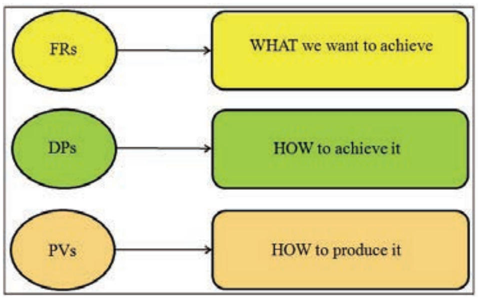

Fig. 2. Explanation of the Different Variables Related to the Domains

The second dimension of the decomposition is hierarchical within the domains. This analysis can be done according to equivalence relations, based on partitioning [11]. The objective is to achieve a collectively exhaustive and mutually exclusive collection of the functions [12,13] to address the relevant situations.
In particular, the AD process drives the decomposition between domains and “qualitatively” defines the project structure. It provides the basis for the selection of the key design variables (DPs) that characterize the design satisfying the FRs. The selection of the DPs is tested against the axioms. The process of matching variables in one domain (e.g., FRs) with other variables in another domain (e.g., DPs), also called mapping represents the road from WHAT to HOW. The objective of this study is to identify through AD the optimal sequence of inquiries necessary to deploy a full LSS competency by highlighting the hierarchy of Aristotle’s approach: certain types of questions need to be asked and answered before others can be asked [14]. Axiomatic Design facilitates the synthesis and analysis of suitable design requirements, solutions, and processes supporting Project-Based Learning.

2. Methodology:

Decisions made during the design stage of product and process development profoundly affect product quality and process productivity [15]. Suh et. al., [16] define certain axioms and rules that need to be satisfied in the process of mapping Design Parameters in the functional space. These axioms characterize 'good designs'. Suh [8] provides an Axiomatic Design framework to describe design objects and a set of axioms to evaluate relations between intended functions (Functional Requirements) and means by which they are achieved (Design Parameters). The two design axioms are the Independence Axiom and the Information Axiom. Tatray and Sohlenius [17] theorize that axiomatics is a design theory that is based on probabilistic concepts. They state that the Independence axiom deals with the coupling of functions in a design and the second, the Information axiom, deals with simplicity and probability of success. Axiomatics can be successfully applied to reliability design. Product reliability is determined at its design stage and must be identified to adequately evaluate the feasibility of the design [18]. The authors state that a design team must detect any potential reliability problems before completion of the product design. The recognition of the need to establish design principles as the fundamental rules of design can be traced back to the nineteenth century when Reuleaux introduced two fundamental design principles [19]. Suh's Axiomatic Design represents one of the contemporary approaches in the development of design principles [8]. The Axiomatic Design principle suggests that there are fundamental concepts that can be generalized and applied to all design solutions.

Axiomatic Design [8], is motivated by the absence of scientific design principles. Suh [8] proposed the use of axioms as the pursued scientific foundation for engineering design. Out of the twelve axioms first suggested, Suh introduced two basic axioms along with six corollaries as design principles that a design needs to satisfy. Suh proposed the following 2 axioms as the universal principles which any 'good' system design should satisfy.

> Axiom 1: Maintain the independence of Functional Requirements It means that in a good design, the independence of Functional Requirements is maintained.
>
> Axiom 2: Minimize the information content of the design. It means that among designs that satisfy axiom 1, the best design is the one that has the minimum information content. Here the information content is a measure of design complexity. So the second axiom indicates that the design simplicity should be pursued given the Functional Requirements can be met.

In this approach, the design is defined as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the Functional Requirements (FRs) in the functional domain and the Design Parameters (DPs) in the physical domain. This is illustrated in Figure 3

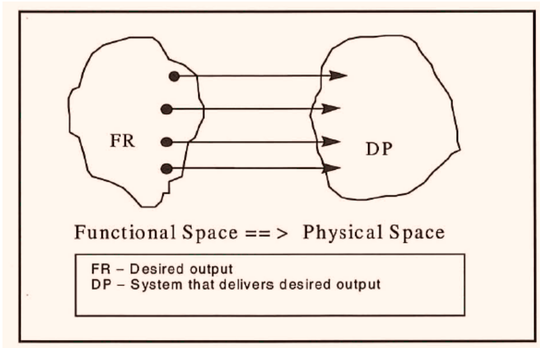

Fig. 3. Axiomatic Design Process

Axiom 1 states that the Design Parameters (DPs) and the Functional Requirements (FRs) are related such that a specific DP can be adjusted to satisfy its corresponding FR without affecting the other Functional Requirements. After satisfying the Independence Axiom, the design simplicity is sought by minimizing the information contents per Axiom 2. In this context, information content is defined as a measure of complexity and is related to the probability of conceived solutions meeting the Functional Requirements. However, the exact deployment of these design axioms might be infeasible due to technological limitations. Under these circumstances, different degrees of design vulnerability are established in the measures (criteria) related to the unsatisfied axioms. A violation of the independence axiom will create coupling of the FRs. An elevated degree of design complexity can exist as a result of Axiom 2 violations and the entity may face doubtful success opportunities even after rigorous optimization phases. Therefore, prior to these efforts, design vulnerability should be eliminated, or at least reduced to the greatest extent practical.

3. Design decomposition and final design for Project-Based Learning training

In the process of Axiomatic Design, [8] has exhaustively dealt with applying the Axiomatic Design principles to the 2nd phase of QFD (HOQ 2) which is the parts deployment phase. Design is defined as an epitome of the goal of engineering, facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations. The engineering design process is typically viewed as a process that takes a set of specified inputs and conceptualizes a design entity that can capably achieve the desired output. Figure 4 is a classical conceptualization of an engineering design process.

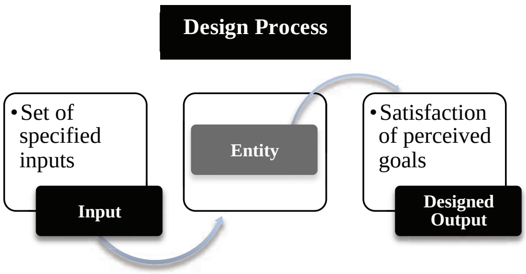

Fig. 4. Design Process

Suh proposes that a typical design process has the following components:

- Problem Definition: Forming a "fuzzy" array of facts and myths into a coherent statement of the question
- Creative process: Devising a proposed physical embodiment of solutions
- Analytical process: Determining whether proposed solution is correct or rational
- Ultimate check: Fidelity of the designed product to the original perceived needs

To successfully achieve a design solution using an input-output model of a design conceptualization process, a design engineer is faced with a set of questions. These design questions are:

- How do you make design decisions?
- Is this a good design?
- Why is this design better than others?
- Is my design rational?
- Can it be made?
- Shall I make this in one piece or two pieces? Why?
- How many Design Parameters (DP's) do I need to satisfy the FR's?
- Shall I abandon this idea or simply modify it?
- I thought this was a good idea - why didn't it work?

Once these questions have been answered, the result is the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the Functional Requirements in the functional domain and the Design Parameters of the physical domain, through the proper selection of DP's that satisfy the FR's. The mapping process is non-unique that can result in an infinite number of plausible solutions. FR's are defined as "a minimum set of independent requirements that completely characterize the design objective for a specific need."

The primary steps to this design methodology is to develop Functional Requirements for an effective Project-Based Learning. Learning environments that are Project-Based have five key features and these features form the basis of the Functional Requirements. These requirements are mapped to the Blooms Taxonomy of cognitive learning [20] to ensure that the key cognitive learning elements are available in the Functional Requirements (FRs) of the Project-Based Learning design. Table 1 maps these elements. The mapping assures that the Project-Based Learning objectives are satisfying the Blooms Taxonomy of cognitive learning.

Table 1. Mapping of Project-Based Learning FRs to Cognitive learning elements

FUNCTIONAL REQUIREMENTS - What we want to achieve	
Learning Objective	Blooms Taxonomy - Cognitive Learning
Determine learning framework	Create
Determine learning schedule	Create
Frame question	Understand
Identify driving Problem	Understand
Apply functional competencies	Apply
Apply discipline context functional tools	Apply
Apply discipline context technology	Apply
Apply problem solving competencies - Groups/Teams	Analyze
Create set of tangible products that address question	Create
Share learning with class	Evaluate

The next step of the design process is to develop the Design Parameters that are to be mapped to the Functional Requirements. These Design Parameters (DPs) are based on the competency chart of the Lean Six Sigma agent in Fig 1. These DPs are represented below. Design parameters answer the question “How to achieve it?” The basis for DPs that satisfy the FRs is Project-Based Learning.

- Process Knowledge
- Initiative, Enthusiasm, Persistency
- Goal Oriented Approach
- Team working
- Leadership
- Communication skills
- Analytical Skills
- Time Management Capacity

Axiomatic Design is defined as the mapping process between the FR's in the functional domain and DP's in the physical domain. Let there be m components represented by a set of independent FR's (Vector FR with m components). DP's in the physical domain are characterized by vector DP with n components.

The design process is choosing the right set of DP's to satisfy the given FR's.

{FR} = [**A**] {DP}

{FR} = Functional Requirement vector, {DP} = Design Parameter vector, [**A**] = Design matrix, and the design matrix [A] is of the form:

$$\overline{[A]} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ \vdots & & & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix} \quad \text{where} \quad A_{ij} = \frac{\partial FR_i}{\partial DP_j}$$

Figure 5 shows the schematic of the design matrix that will aid the complexity analysis of the Project-Based Learning model. The design matrix relationships are presumed binary for this analysis. A_{11} is 0 when FR_1 is not related to DP_1 and 1 when it is.

The objective of the Axiomatic Design process is to satisfy a valuable learning experience (learning) through a blended classroom (teaching)

FR TO DP DOMAIN CONVERSION

FUNCTIONAL REQUIREMENTS - What we want to achieve		DESIGN PARAMETERS - How to achieve it - Basis is Project Based Learning								
Learning Objective	**Blooms Taxonomy - Cognitive Learning**	Process Knowledge	Initiative, Enthusiasm, Persistency	Goal Oriented Approach	Team working	Leadership	Communication skills	Analytical Skills	Time Management Capacity	Computer Skills
Determine learning framework	Create		1			1				
Determine learning schedule	Create		1						1	
Frame question	Understand	1				1	1			
Identify driving Problem	Understand	1		1	1		1	1		
Apply functional competencies	Apply	1								
Apply discipline context functional tools	Apply	1								
Apply discipline context technology	Apply									1
Apply problem solving competencies - Groups/Teams	Analyze	1			1			1		
Create set of tangible products that address question	Create	1		1	1			1		
Share learning with class	Evaluate		1		1	1	1			

Fig. 5. Schematic of design matrix for PBL model

4. Assessment of design Complexity

In an ideal design, the independence of the Functional Requirements with respect to the Design Parameters is maintained. This proposal predicates that in a sound design process, where the FR's are mapped to the DP's via the design matrix [**A**], the ability to select independent targets for the DP's is dependent on the mappings of the DP's back to the FR's. In a good design this mapping should be satisfied by a singular DP to FR relationship or in other words, a particular DP should affect only its referent FR. Such a design is an uncoupled design for a square design matrix. A review of the design matrix shows that there are 10 functions and 9 Design Parameters. This implies a violation of the independence axiom and would require at least two Functional Requirements to map to one Design Parameter for the design to satisfy. The process of Axiomatic Design, Suh [8] requires that each FR should map to at least one DP for the function to be delivered. The design matrix above shows this condition is met. FRs are related to at least one DP. Although the axiom of independence is violated due to multiple complex relationships exhibited by the lack of a square matrix and presence of off diagonal relationships.

Resolution of the two design independence axioms can be done through a design optimization procedure where rearrangement of the relationships between function requirements and Design Parameters. Design independence through relationships of one FR related to one DP is expressed by a diagonal matrix. Assessment of the matrix in Figure 5 shows an absence of a diagonal matrix. Even though the design independence axiom is violated, its affect can be minimized and the design process can be controlled by determining if there is a possibility of rearranging the design matrix to form a lower matrix. This lends the hierarchical optimization of Design Parameters and working through the lower matrix where a higher level parameter is optimized and fixed and its effect is determined at the second level and the next Design Parameter is now restricted by the first Design Parameters optimized value while the second Design Parameter is now optimized within the constraints of the first Design Parameter. This multi level hierarchical (MLH) modelling technique has been applied by Trewn and Yang [21] in the reliability modelling environment and later utilized to determine the design vulnerability (dependence) of systems reliability where an independent diagonal matrix is absent [22]. This methodology of multi level hierarchical (MLH) modelling is exhibited in Figure 6.

Unoptimized Dependent Design

	DP_1	DP_2	DP_3	DP_4	DP_5	DP_6
FR_1		1	1			
FR_2		1				
FR_3	1		1	1	1	1
FR_4	1				1	

Independence Axiom Violations

1. Not a square matrix

AND

2. Not a diagonal matrix

Optimized Dependent Design

	DP_2	DP_3	DP_4	DP_5	DP_1	DP_6
FR_2	1					
FR_1	1	1				
FR_3		1	1	1	1	1
FR_4				1	1	

FR_4 remains suboptimized and unsatisfied

(solid grey)	Independence
(hatched)	MLH Optimization - Freedom for optimization
(dotted)	Constrained by higher level DP optimization

Fig . 6. MLH - Optimizing independence axiom violations

Figure 6 depicts an opportunity to optimize Design Parameters in a hierarchical step process. As a higher level Design Parameter is optimized to provide a function, its effect on the next lower level function is known and the other Design Parameters linked to that function can be manipulated to further provide this level function and so on. Based on the example in Figure 5, DP_2 is optimized to provide Function 2. Now that DP2 is constrained, DP3 is optimized till Function 1 is provided as desired. This process is continued stepping through the design hierarchy.

Hierarchy of optimization:

1. Optimize FR_2 with DP_2
2. Optimize FR_1 with DP_3 freedom within constraint of DP_2
3. Optimize FR_3 with DP_4, DP_5, DP_1 freedom within constraint of DP_3 and full freedom of DP_6
4. ***FR4 remains sub-optimized as DP_5 and DP_1 are constrained***

This design will require decoupling of FR4 from DP5 and DP1 and subsequent assignment of an independent DP as FR4 is not optimized and it determines the design vulnerability.

This MLH design optimizing procedure can be extended to the design matrix of the Project-Based Learning model to handle design independence axiom violations. Figure 7 exhibits one such optimization procedure.

This design analysis using the Axiomatic Design independence axiom results in the following design statements:

1. Independent Functional Requirements: “Apply discipline context technology” and “Determine learning schedule” can be optimized by independent Design Parameters
2. MLH optimized Functional Requirements: “Determine learning framework”, “Share learning with class”, “Frame question, “Apply problem solving competencies - Groups/Teams”, “Identify driving Problem” are Functional Requirements that are not independent but can be optimized using MLH procedures
3. ***Design Vulnerabilities***: “Create set of tangible products that address question”, “Apply functional competencies”, “Apply discipline context functional tools” are highly constrained and coupled Functional Requirements that need decoupling using Design Parameter isolation techniques such as TRIZ.

FUNCTIONAL REQUIREMENTS - What we want to achieve		DESIGN PARAMETERS - How to achieve it - Basis is Project Based Learning								
Learning Objective	Blooms Taxonomy - Cognitive Learning	Computer Skills	Time Management Capacity	Initiative, Enthusiasm, Persistency	Leadership	Communication skills	Team working	Process Knowledge	Analytical Skills	Goal Oriented Approach
Apply discipline context technology	Apply	1								
Determine learning schedule	Create		1	1						
Determine learning framework	Create			1	1					
Share learning with class	Evaluate			1	1	1	1			
Frame question	Understand				1	1		1		
Apply problem solving competencies - Groups/Teams	Analyze						1	1	1	
Identify driving Problem	Understand					1	1	1	1	1
Create set of tangible products that address question	Create						1	1	1	1
Apply functional competencies	Apply							1		
Apply discipline context functional tools	Apply							1		

Independence
MLH Optimization
Constrained by higher level DP optimization

Fig. 7. MLH Optimized Design

4. Conclusion and remarks

The Axiomatic Design methodology supports and facilitates the synthesis and analysis of suitable design requirements, solutions, and processes to optimize a product or a process design. In this study, the AD method has been applied to the optimization of Project-Based Learning by linking learning outcomes of Lean Six Sigma training with the availability of resources all the teaching processes. Axiomatic Design literature is more and more dealing with optimization of processes and transactional ones, including educational processes. No relevant secondary sources and scholarly articles have been found regarding the application of AD to Project-Based Learning, and in particular to the specific application of PBL to Lean Six Sigma training. A deep knowledge of the problem solving and matrix design methodologies can be extremely supportive to solve technical issues as well as to develop training methods by using a creative process to conceptualize and optimized them. While the methodology of multi level hierarchical (MLH) modelling showed in this article has been able to optimize the training product, some of the Functional Requirement are highly constrained and coupled Functional Requirements that might need decoupling using Design Parameter isolation techniques such as TRIZ. It is in fact easy to find in literature examples of Axiomatic Design use in conjunction TRIZ, either using the TRIZ from the perspective of Axiomatic Design as well as adapting the Axiomatic Design to the TRIZ frameworks [23]. The same can be said for what regards the tool mostly used in Quality Function Deployment (QFD), often used to convert market information into product strategies for business [24]. Axiomatic Design represents a powerful tool to serve professional training organizations as well as the Education Industry in improving the performances by projecting new effective and reliable systems. Further studies can be developed on the application of such methodology to pedagogical approaches, teaching and learning methods. Structured design methodology finds its application also to daily life where searching solutions to concrete problems often deal with the psychological inertia, with the tendency to think and follow the same known mental schemes [25].

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