Investigations on Interrelations Between Design for X-Guidelines and Product Life cycle Phases—An MDM-Based Approach

M. Manojkummar, K. E. K. Vimal, Abdul Zubar Hammed, and K. Jayakrishna

Abstract The development of a comprehensive system for understanding the early stages of product development process helps in preventing excessive changes in the advanced phases of the life cycle. Increasing the transparency among product goals and potentials, arising from different life cycle phases is essential to enhance the process of product planning. Therefore, the primary objective of this work is to explore how the network of DFX guidelines can be characterized, and thereby, interrelations among the life cycle phases can be studied based on their association with different DFX guidelines. Conclusions about which life cycle phase plays an important role in pursuing and meeting certain life cycle-oriented goals and how these phases are interlinked are also drawn. The analyses were carried out using a Multiple Domain Matrix (MDM)-based approach, which includes deriving respective Design Structure Matrices (DSMs) to allow the detection of central life cycle phases and DFX guidelines based on structural metrics addressing the centrality of elements.

Keywords Design for X · DFX-X · Life cycle · Product planning · MDM

1 Introduction

Organizations believe that effective product life cycle (PLC) management has its impact on product design and development but beyond that, they also have their effect on the manufacturing strategy. A product life cycle comprises entire life cycle of the product starting from concept, engineering design, manufacturing till its disposal. The process of PLC management also includes several decision factors such as people, data, marketing and enterprise strategies and integrating these to attain

M. Manojkummar · K. Jayakrishna (✉)
School of Mechanical Engineering, VIT University, Vellore, Tamil Nadu, India
e-mail: jayakrishna.k@vit.ac.in

K. E. K. Vimal
Department of Mechanical Engineering, National Institute of Technology, Patna, Bihar, India

A. Z. Hammed
Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

L.-J. Yang et al. (eds.), *Proceedings of ICDMC 2019*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-3631-1_50

sustainability. Though the PLC policies are used for more than several decades, still the gap between meeting exact customer need and product characteristics exists. The product should possess certain characteristics in order to meet both business objectives and customer needs. Such products are developed by transforming a feasible idea into a product by selecting viable technical and economic strategies [1]. The overall analysis of a product life cycle helps in determining where the product will succeed and fail during its life cycle. By analyzing the product characteristics, the factors contributing in making the product successful could be determined across each phase of the life cycle. Even before the product reaches its initial PLC stage, it undergoes a pre-manufacturing phase where numerous ideas for the product are projected and are analyzed by considering various factors that will make the product a success in the market. This pre-manufacturing phase should be as short as possible because the first launch of the product among competitors has an impact on the revenue generated by the company by that product [2]. Every product has different PLC stages based on its life cycle period, target market, innovation, etc.

PLC stages are generally classified as development, introduction, growth, maturity and decline. In this study, these life cycle stages are taken with specification to manufacturing of a product such as raw material extraction, material processing, design, manufacturing, distribution and sales, product use and end of life stages [3]. PLC stages have their roles in determining product characteristics. Raw material extraction focuses on the processes and the guidelines followed while selecting and obtaining the materials for production; these are the materials which are taken as input in every process. Based on the extracted raw material, the parameters considered in production are selected and evaluated in material processing stage. The design phase plays a major role in determining various product features [4], and based on the output of the design phase, process planning is made; these processes are dealt in the manufacturing phase. The marketing activities such as demand forecasting and the process involved in taking customer order and delivering the product to the customer are taken into account in distribution and sales phase. The customer response and feedback after the use of the product by the customers will be considered in product use phase; this phase has the character of being uncertain. The product delivered by the company can either be success or failure and the factors such as ‘design for serviceability’ and ‘design for maintainability’ have its relations with this phase. The end of life stages phase deals with the activities that are carried out after the product is damaged such as recycling and refurbishing.

From the above context, the complexity of the products’ life stages can be understood from each stage of PLC. Every stage involves many processes, and every process has several alternatives such as design, machine and material alternatives. Design for X (DFX) where ‘X’ stands for the different attributes such as cost, the environment of use and material is considered across the PLC stages. The resultant product characteristics will have maximum matches with that of customer requirement. By considering this DFX across each stage of product development, determining the interdependencies between them will help to improve sustainability of the product. DFX also helps in improving product quality, reliability, design flexibility, efficiency, productivity and reducing waste, prototyping cost and overall life cycle cost.

The objective of this study is to reveal the interrelationships that exist between DFX guidelines and PLC stages and to determine the product characteristics based on the interdependencies of DFX guidelines and PLC stages. The DFX guidelines involved in a process are interdependent, and different DFX can have its impact on the same product characteristics. For example, the ‘design for cost’ and ‘design for carbon footprint’ guidelines have their impact in raw material extraction phase of PLC and also interrelation among DFX such as ‘design for material’ and ‘design for manufacturability’ are related, based on the material, manufacturing process and but the process parameters may vary at each phase. This forms complexity in the product development process due to the presence of numerous networks of dependencies existing between the DFX guidelines and also among the PLC stages. By improving the transparency in the interrelation networks, guidelines affecting a particular phase of PLC and how it can alter the resultant product characteristics can be identified. The product development stage constitutes certain uncertainties as both customer and company objectives need to be achieved. It means that the relation between DFX and PLC stages has to be evaluated together [5]. The complexity of the system depends on the number of factors contributing and controlling the system, where the product development stage can be controlled by a number of DFX in each PLC phases [6]. In order to deal with such complex network relation identification, in this study, Multiple Domain Matrix (MDM) technique is used. An MDM is composed of Design Structure Matrix (DSM) and Domain Matrix Multiplication (DMM). DSM deals with determining the intra-relations among several factors of the strategy considered and DMM deals with determining the intra-relations among different domains involved in the strategy [7].

The above-described objectives can be split down into two major goals as

1.1 Goal 1

To improve the transparency in determining product characteristics, as it is based on the interrelations among different PLC stages with respect to DFX guidelines and to conclude which phase of the life cycle plays an important role in meeting the product goal. The processes are classified as major goals because different PLC stages can address the same product characteristics with different DFX guidelines and identify the networks making the product development phase more transparent.

1.2 Goal 2

To explore the network of DFX guidelines, interrelations among the life cycle phases can be arrived based on their association with different DFX guidelines. This is also a major goal because a DFX guideline could address different PLC stages with respect to product characteristics and identify the central DFX guidelines which have a prime impact over the PLC stage that would improve the early product development strategies.

2 Methodology

The complexity of the DFX guidelines and PLC stages networking activity could be analyzed using MDM technique in a feasible way. As discussed, the MDM is comprised of DSM and DMM; therefore, it gives both inter- and intra-relations between the factors considered, which helps to achieve the goals of this study. The results of these MDMs also help to bring benefits to both company and customer by providing sustainable consumption and production of products.

DSM is an $m \times m$ matrix having corresponding factors enlisted in both rows and columns and gives both directional and non-directional results of interdependencies of the factors. DMM is an $m \times n$ matrix which determines the network of the relationship between different domains. DMM is constrained for comparing only two domains at a time, whereas MDM can be used to compare multiple domains with both inter- and intra-relationships in combination with DSM [8]. This structured analysis makes the technique more feasible to determine the interdependencies of higher order complex networks like this study. As mentioned, this combination of DSM in MDM paves way for solving several levels of detailed problems and is considered in this study to its simplest form in order to reduce the complexity of the process. This study gives a generic approach of determining interrelationships between DFX guidelines and PLC stages with respect to product characteristics which can be taken as a base model and customized based on the product decided by the OEM.

From the identified major goals of the study, it shows that DFX guidelines are common in both the goals which make it a major decision-making factor of the process involved in this study. There are numerous DFX guidelines available [9], but in this study, a representative set of DFX guidelines across the PLC stages was selected based on the theoretical analysis in consultation with subject experts and a brief literature review is also made on selecting the DFX guidelines. The DFX guidelines considered are shown in Table 1. From the selected DFX guidelines, certain product characteristics could be determined such as material, surface finish, quality and reliability but as the objective of this study is to determine product characteristics based on interrelation with PLC stages, the relation network between PLC stages and DFX guidelines is plotted using DMM matrix. This network is made based on the analysis with the guidance of subject experts. For example, ‘design for material’ guideline implies that material has a huge influence on the product development. Different manufacturing strategies such as equipment selection and process parameters are required based on the material selected for manufacturing the product [10] which shows the relation of ‘design for material’ guideline with PLC

Table 1 Analyzed DFX guidelines

Design for **cost** [14]	Design for **environment of use** [15]	Design for **carbon footprint** [15]
Design for **material** [10]	Design for **equipment selection** [10]	Design for **layout** [16]
Design for **reduce** [17]	Design for **material handling** [10]	Design for **manufacturability** [18]
Design for **variants** [10]	Design for **strength** [10]	Design for **safety** [15]
Design for **ergonomics** [19]	Design for **quality control** [16]	Design for **yield** [16]
Design for **assembly and disassembly** [18]	Design for **productivity** [16]	Design for **six sigma** [20]
Design for **efficiency** [16]	Design for **ease of fabrication** [19]	Design for **supply chain** [21]
Design for **logistics** [21]	Design for **sustainable packaging** [15]	Design for **serviceability** [16]
Design for **maintainability** [18]	Design for **utilization** [16]	Design for **recycle** [17]
Design for **refurbish** [18]	Design for **remanufacture** [18]	Design for **disposal** [17]
Design for **validation** [20]	Design for **robustness** [16]	Design for **standards** [20]

phases of 'raw material extraction,' 'material processing,' 'design,' 'manufacturing' and 'end of life stage.'

In order to determine inter- and intra-relations between the DFX guidelines, a DSM is made with the context of selected DFX guidelines (DSM for DFX) shown in Table 2. For instance, the 'design for cost' guideline has intra-relation with other DFX guidelines such as 'design for material,' 'design for strength' and 'design for supply chain.' Similar to DSM of DFX, another DSM is made for determining the relationships in PLC stages (DSM for PLC). For example, design phase has its influence over manufacturing, product use and end of life stages which shows that the process of one phase affects the process to be carried out in subsequent phases, concluding that there must be clarity in the evaluation of selecting the process strategy carried out in each stage.

Table 2 Part of DMM for DFX guidelines and PLC stages

	Cost	Environment of use	Carbon footprint	Material	Equipment selection	Layout
Raw material extraction	∞	∞	∞	∞		
Material processing	∞	∞	∞	∞	∞	∞
Design	∞			∞		

Fig. 1 Analyzed MDM of DFX guidelines and PLC stages

	DF-X Guidelines	**PLC stages**
DF-X Guidelines	DSM for DFX	DMM for DFX to PLC
PLC stages	DMM for PLC to DFX	DSM for PLC stages

As the objective of this study is to determine product characteristics based on the combination of both DFX guidelines and PLC stages and their interdependencies, the analysis was carried out with data comprising interrelationships of DFX guidelines and PLC stages in regard of product characteristics. An MDM is made with DSM of DFX and DSM of PLC in main diagonal and DMM linking DFX and PLC in off-diagonal of the matrix.

As a summary of the procedure described, Fig. 1 shows the matrix representation with DSMs and DMMs.

3 Results and Discussions

Table 2 shows the DMM matrix of DFX guidelines and the PLC stages, where the relation network of DFX guidelines shown in Table 1 and PLC stages considered are plotted. The '∞' sign shows that there is a relation between factors mentioned in row and column.

Table 3 shows the DSM matrix for DFX guidelines where the interdependencies of DFX guidelines are identified. DSMs have their wide application in automobile, electronic and other such fields to solve problems [11]. Table 4 shows the DSM matrix for PLC stages where the interdependencies of PLC stages are identified.

Based on these DSMs and DMMs, the MDM is formulated and is shown in Fig. 2. In order to evaluate the complex interdependencies of DFX guidelines and PLC stages together in determining product characteristics, MDM is made. This MDM is further

Table 3 Part of DSM for DFX guidelines

	Cost	Environment of use	Carbon footprint	Material	Equipment selection	Layout
Cost	*0*			∞	∞	∞
Environment of use		*0*	∞	∞		∞
Carbon footprint	∞	∞	*0*	∞		
Material	∞	∞	∞	*0*	∞	
Equipment selection	∞	∞		∞	*0*	∞
Layout	∞					*0*

Table 4 Part of DSM for PLC stages

	Raw material extraction	Material processing	Design	Manufacturing
Raw material extraction	*0*	∞		
Material processing	∞	*0*		
Design			*0*	∞
Manufacturing			∞	*0*

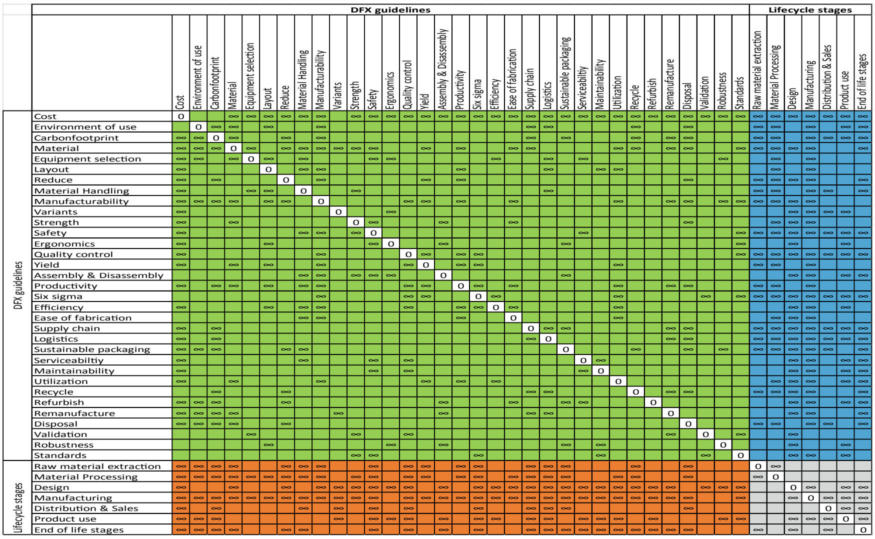

Fig. 2 MDM formulated from DSM and DMM

solved using ‘clustering’ technique where the scattered MDM matrix is clustered into groups based on their relation with respective DFX guidelines and PLC stages. From the literature review made on clustering technique, it is evident that this technique has been used for several similar decision-making strategies such as machine learning, pattern recognition and information retrieval which has given a feasible solution for higher order complex networks [12]. The clustering technique used can also be termed as multi-objective optimization problem because of its ability to analyze the multiple processes governing factors such as this study. Based on the clustered groups, the relation of every DFX guidelines with PLC stage can be determined and the product characteristics could be determined in the early product developmental stage.

4 Conclusions

Based on the analysis of MDM matrix, the interdependencies of PLC stages in association with DFX guidelines were identified, and from the clustered matrix, the phases with high impact factor on determining product characteristics were determined. The results of the study show that 'raw material extraction' phase and 'material processing' phase are coupled which means that both of them have mutual sharing of process parameters in determining product characteristics. Followed by them, 'design' phase has relation with 'manufacturing,' 'product use,' 'end of life stages' and 'manufacturing' phase with 'design,' 'distribution and sales,' 'product use' and 'end of life stages.' 'Distribution and sales' phase is interrelated with 'product use' and 'end of life stages' such as other phases also have their contribution in determining product characteristics in relation with the considered 33 DFX guidelines.

By the use of clustering technique in MDM approach of finding the interdependencies of DFX guidelines and PLC stages, a designer could get the common generic algorithm for developing different future products with improved development speed and efficiency. In comparison with other analyzing tools such as Gantt chart, this approach is more user-friendly for integrating with computer software [13]. As the number of decision-making factors increases, the complexity of the problem also increases which makes the manual calculations a fuzzy approach. Also, the trend of digitization and automation of operations make it simpler to feed the data to computers. The futuristic problem-solving softwares are also making their way in industries, where these combinations will further simple down the process. This study gives an application of MDM in a complex scenario in determining product characteristics by analyzing the interdependencies of DFX guidelines and PLC stages. This approach could be used by industries with respect to a product development phase which would give a feasible solution. By implementing this methodology in industry orientation, further areas requiring more optimization can be identified and further study could be carried out in the identified region.

References

1. Jiang R (2015) Introduction to quality and reliability engineering. Springer, Berlin
2. Mälkki H, Alanne K (2017) An overview of life cycle assessment (LCA) and research-based teaching in renewable and sustainable energy education. Renew Sustain Energy Rev 69:218–231
3. Vinodh S, Jayakrishna K (2013) Assessment of product sustainability and the associated risk/benefits for an automotive organisation. Int J Adv Manufact Technol, 1–8
4. Kim KY, Psenka CE, Haapala KR, Schmidt-Jackson K, Okudan-Kremer GE (2017) Constructionism in learning: sustainable life cycle engineering project (CooL: SLiCE)
5. Joore P, Brezet H (2015) A multilevel design model: the mutual relationship between product-service system development and societal change processes. J Clean Prod 97:92–105
6. Neumann M, Sadek T, Labenda P, Herzog M (2012) Integrating structure and uncertainty modelling using multiple-domain-matrices. In: DS 70: proceedings of DESIGN 2012, the 12th international design conference, Dubrovnik, Croatia

7. Adham S, Chang J, Liao HJ, Hung J, Hsieh TH (2014) The importance of DFX, a foundry perspective. In: 2014 IEEE international test conference (ITC). IEEE, pp 1–6
8. Hamraz B, Caldwell NH, Clarkson PJ (2012) A multidomain engineering change propagation model to support uncertainty reduction and risk management in design. J Mech Des 134(10):100905
9. Sassanelli C, Pezzotta G, Sala R, Correia A, Terzi S (2017) Testing the methodology to generate Design for Product Service Supportability (DfPSS) guidelines and rules: an application case. Procedia CIRP 64:265–270
10. Chan FTS, Ip RWL, Lau H (2001) Integration of expert system with analytic hierarchy process for the design of material handling equipment selection system. J Mater Process Technol 116(2):137–145
11. Zhang ZC, Hu XP, Xi CQ (2012) A dsm-based multiple-domain modeling of product information. In: Applied mechanics and materials, vol 201. Trans Tech Publications, pp 947–950
12. Cooper C, Franklin D, Ros M, Safaei F, Abolhasan M (2017) A comparative survey of VANET clustering techniques. IEEE Commun Surv Tutorials 19(1):657–681
13. Bartolomei JE, Hastings DE, de Neufville R, Rhodes DH (2012) Engineering systems multiple-domain matrix: an organizing framework for modeling large-scale complex systems. Syst Eng 15(1):41–61
14. Berg JS, Bogacz SA, Caspi S, Cobb J, Fernow RC, Gallardo JC, Paul K (2006) Cost-effective design for a neutrino factory. Phys Rev Spec Top-Accelerators Beams 9(1):011001
15. Kenny T, Gray NF (2009) Comparative performance of six carbon footprint models for use in Ireland. Environ Impact Assess Rev 29(1):1–6
16. Wu X, Chu CH, Wang Y, Yan W (2007) A genetic algorithm for cellular manufacturing design and layout. Eur J Oper Res 181(1):156–167
17. Shin JH, Kwon SM (2006) On the lobe profile design in a cycloid reducer using instant velocity center. Mech Mach Theory 41(5):596–616
18. Boothroyd G (1994) Product design for manufacture and assembly. Comput Aided Des 26(7):505–520
19. El-Hami M, Glynne-Jones P, White NM, Hill M, Beeby S, James E, Ross JN (2001) Design and fabrication of a new vibration-based electromechanical power generator. Sens Actuators, A 92(1):335–342
20. Linderman K, Schroeder RG, Zaheer S, Choo AS (2003) Six sigma: a goal-theoretic perspective. J Oper Manage 21(2):193–203
21. Seuring S, Müller M (2008) From a literature review to a conceptual framework for sustainable supply chain management. J Clean Prod 16(15):1699–1710