ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

Engineering Changes in Product Design – A Review

K Tirupathi Rao, G Shobha, B Swetha Associate Professor^{2,3}, Department of ECE, gshobha.ece@anurag.ac.in, bswetha.ece@anurag.ac.in Anurag Engineering College, Kodada, Telangana

Abstract. Changes are fundamental to product development. Engineering changes are unavoidable and can arise at any phase of the product life cycle. The consideration of market requirements, customer/user feedbacks, manufacturing constraints, design innovations etc., turning them into viable products can be accomplished when product change is managed properly. In the early design cycle, informal changes are accepted. However, changes become formal when its complexity and cost increases, and as product matures. To maximize the market shares, manufacturers have to effectively and efficiently manage engineering changes by means of Configuration Control. The paper gives a broad overview about 'Engineering Change Management' (ECM) through configuration management and its implications in product design. The aim is to give an idea and understanding about the engineering changes in product design scenario to the new researchers. This paper elaborates the significant aspect of managing the engineering changes and the importance of ECM in a product life cycle.

Keywords: Change Management, Configuration Management, Product architecture, Product Structure, Engineering Change Management (ECM), Modular Product, Design Structure Matrix(DSM), Version control, Work flow management, Information management

1. Introduction

In today's market scenario, change environment has become a threat to the manufacturers to produce a high quality product at the lowest cost with the minimal lead-time. So designers are forced to retain the existing design significantly to reduce the cost and the manufacturing lead-time. New design has been evolved through modifications and changes to the existing design [1]. Engineering changes influences greatly on product development and production activities, making product development costly and time consuming [2]. In the early decades, Organizations shown some reluctance in adopting/implementing the change management system to manage the engineering changes, but due to industrial revolutions and IT dominations, past few decades it has been seen evidently that firms take it as an opportunity for the innovation and creativity, change management is taken as a driving force for incremental product improvement. [3,4]. Keeping in view the above, knowledge attained from engineering changes arise frequently for continual improvement of the system/product and determines approximately 70 to 80% of the final product cost [5].

The paper is structured in such a way that it discusses about the topics namely, Change Management, Configuration Management, Comparison between Change Management and Configuration Management, Engineering Change, Engineering Change management, Categorization of engineering changes, Product Architecture, Product Classification, Change propagation, Engineering Change Process, Methods and Tools to support ECM, Version control, Workflow Management, Information system, System modelling and language support for ECM.

Configuration Management (CM)

Configuration Management (CM) is an engineering process for ensuring the requirements, design and operational information by product's functional, performance and physical attributes throughout its life cycle. CM enables the management of artefacts from the initial concept through design, implementation, testing, building, release and maintenance. Product's change is a fact and inevitable. The lack of implementation of CM believes to have serious catastrophic consequences such as equipment failure or loss of life. CM aids to validate that the changes are proposed, evaluated and implemented in a standardized systematic approach, which ensures consistency and evaluates predictable impact on the system. CM verifies that changes are incorporated and systems reflect their proper configuration. It can store, track and update all system's information in the form of component, system and sub-system. A CM program includes (a) Management and Planning, (b) Configuration Identification, (c) Configuration Control, (d) Configuration Status Accounting and (e) Configuration

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

Verification and Audit (figure 1). The CM process widely used to control the complex systems throughout its life in defence and military engineering organizations to manage changes in weapon systems, military vehicles, aircraft and aerospace applications, IT service management etc. with the help of respective PLM tools & technology [10] [11] [12].



Figure 1: Configuration Management Model [13]

2. Change Management

Change Management evolved during the year 1980's as a concept driven by the fortune 50 companies [6]. General Electric was the first one to adopt the Change management philosophy [6]. Globalization and innovation of technology resulted in demanding need for change, and therefore change management gained visibility [6][8]. Later, companies realized that Change management is beneficial in terms of cost savings [6]. However, adaptability becomes difficult because of the organization structure, culture and routines, which are resistant to change the current environment of the organization rapidly. Hence, the development of change started and then the tools and processes to implement this change emerged. Due to ever-growing changes in business environment, organizations must learn to bring the essential ability in the workplace. Organizations should quickly respond and adapt to change to create a competitive edge, if not it will go behind over to the other companies. Most R&D organizations including Top firms are currently introducing the Change Management philosophies in order to develop and grow their home-grown to cater their growing needs [6]. Most of the Original Equipment Manufacturers have their dedicated team of Change Management Board and Process for implementing changes in their product life cycle [9]. Change Requests are initiated by the different disciplines of same group or by vendors / suppliers and then those changes are reviewed, approved and implemented by CMB [7] [9].

3. Comparison between Configuration and Change Management

Configuration Management (CM) ensures that the systems or products comply with design specification i.e. product family and architecture. Configuration Management System manages and focuses on the changes related to product specification. Whereas change management ensures that, the changes are implemented within the priorities and constraints. Change management system manages the type of changes and ensures that change request is acknowledged, processed/analyzed and approved or rejected. The purpose of the Change Management System is to implement the approved changes into the project.

Three main aspects of configuration management are – version control, change control, and reports.

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

Changes Control is an element of configuration management, which focus on identify, assessment/impact study, approval, implement & review the changes throughout the lifecycle for the better quality products [13][14][15][16]. The relationships and inter-dependencies among Configuration Management, Change management, Release management & Resource management for productivity enhancement and also for the success of an organization are shown in figure 2 [17].



Figure 2: Relationship between change management and configuration management [15]

4. Engineering Change (EC)

Engineering changes are considered as a normal part of the product life cycle, which is modification to the component of a product, normally takes place, when the product enters the production stage [18]. Engineering change (EC) can also be defined as "Alteration/modification" made to a product structure/bill of materials by adding or deleting an item (component, assembly/sub-assembly etc.), interchanging an item with another, or changing the procedure of an item. In addition, modifications made in the physical characteristics or performance, functional and maintenance of a technical artefact" [19]. Engineering changes can infuse instability into a previously steady operation, changing entities rapidly and severely [20]. It is further classified into three categories, named as immediate, mandatory and convenient change, which represents different degree of urgency for engineering change implementation [21]. ECM consumes 30 to 50%, sometime up to 70% of the production capacity [22] and represents 20 to 50% of manufacturing tool cost [23]. Some other reports suggest that engineering changes usually consume around one third of the engineering design capacity [24, 25].

5. Engineering Change Management (ECM)

ECM controls the process of making modifications or alterations to products [27], used to track all the changes with reference to Material master, Bill of Materials, routing etc. and emphasizes the need to co-ordinate communication, scheduling and resources [28]. If engineering changes are managed effectively, it ensures that the latest version of product, modifications and process data are ready and available at the time needed. The objective of ECM is to address the changes evolved during the product development phase and controls the occurrence of changes to reduce the loss in terms of cost, time, quality and customer satisfaction. For the better management of the changes, three strategies have been proposed in the literatures [29, 30] and five attributes / guidelines are listed [26]. Changes have to be found out or detected as early as possible to reduce the impact of changes. Evaluate the impact of changes and prioritize the changes as per the impact value effectively. Then changes should be implemented in the less time, incurring lower cost and with better quality.

6. The categorization of engineering changes

Numerous studies have been conducted to evaluate the nature and importance of engineering changes. Engineering changes can be mainly classified into two categories: - Emergent changes and Initiated changes. Emergent changes arise from the product itself due to the error during the design process. These changes are also termed as an unintended changes, occurs when some aspect of the system design requires changing because of errors [31]. The reasons of emergent changes are error rectification and safety etc. Initiated changes are originating from the external source. Initiated

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

changes are those intended by the stakeholder. In this perspective, innovation is considered as a part of initiated changes for product enhancement. The reasons of initiated changes are customer, legislation, production, cost reduction, performance, maintainability, technological progress and durability etc. To manage engineering changes, different approaches have been suggested in the literature. These approaches can be divided into three groups [32]. The first group pursues the improvement of engineering changes handling through systematic engineering change processes [21, 27]. Second group attempts to create more changeable products by managing the future changes [33, 34] and last group predict the outcome of undesired changes by modelling techniques and its probable propagation [35, 36].

7. Product Architecture

As per ISO 42010 – 'Architecture' defined as "the fundamental conception of a system in its environment embodied in its elements, their relationships to each other and to its environment, and the principles guiding its design and evolution"





The product architecture in this context defined as the arrangement of the functional elements of a product into several physical building blocks, including the mapping of the functional element to physical components and it is having a strong influence on the success of product [38]. Architecture can influence the product change, product variety, component standardization and product performance [39, 40]. The product architecture mainly characterize by integral or modular type of architecture [41, 42]. In real design circumstances, always there is a trade-off between the integral and modular architecture [44].

Complex (Integral) product architecture

In general, Integral architectures typically connect or associate subsystems with close synchronized relationships and having distinctive features that cannot be easily coupled to other products/systems. Products with integral architecture are least customized, tend to have nonstandard and complex interfaces which are built explicitly for a particular product [39] [46] [47].

Modular product architecture

By contrast, Modular architectures are having a customized with highly standardized interfaces and interoperability for standard connections to any systems/sub-systems. [43] [48]. Module for the systems or products can be created easily as long as it maintains the interoperability and standard interfaces [49]. Upgrading / replacing any module(s), components or sub-systems in this architecture can be easily done without affecting the other components or sub-system. Adopting Modular product design during preliminary design phase will considerably reduce design changes in later stages of Product family

Product family defined as the multitude products with distinctive characteristics and function using common parts/components. The advantage of developing a product family is that it enables a company

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

to offer a great variety of products that are highly differentiated, yet sharing substantial fraction of their components [52]. Product family design is extensively practiced in the industry as a costeffective approach to satisfy the increasing market trend towards smaller batch and more variety orders [53, 54]. In the product family, each product is different from one another and the common parts are used in number of product models. When a particular subassembly is used on a variety of products, saving can be possible – a process termed "Modularizing Product Families" [55]. Product platforms are means to control variety [56]. Part family is a set of parts that serve a related set of market applications - they are functionally similar, and share a common technology base, and lead to better processes for life-cycle design [57].

8. Change propagation

Change propagation is a phenomenon by which one change triggers a series of others changes [58], can potentially distract the manufacturing process [59]. Change propagation can be considered as the cause-effect, cause-effect pattern [60]. Change propagation is an issue that affects both the product and the organization [61]. The initiated change is the primary cause of the propagation and the effect of that change becomes the cause of the subsequent stage. Engineering change propagation can be better understood by the change propagation model in figure 4. The EC1 is the primary cause for the EC2 and triggers a series of other changes. In the products, components are interconnected through the parameters such as geometry, spatial, material, function and behavior. Therefore changing in any one of these parameters may initiate changes in the several other parameters of the system [62, 63]. Second-order change propagations are most likely to propagate and are difficult to foresee at the time of change [63]. It is not necessary that the changes can propagate only to those components which are directly linked to each other but also to other components which has indirect connection.



Figure 4: Change propagation model [26]

9. Engineering Change Process

In order to control the consequences of engineering changes, many companies have adopted the formal engineering change procedure as shown in the Figure 5. The process gets it ignition from the so called change trigger. A well-founded change request can be raised by the firm's employee or by the external source to carry out the engineering change. Then the potential solutions to the engineering change request should be identified and impact & risk assessment should be carried out to prioritize the possible solutions. It is the most critical phase in the engineering change process to evaluate the possible impact of changes. Impact upon the product itself and the effect on the development process must be considered during this phase. Selection and approval before the implementation of such changes must be done by the change board/committee. Finally the approved solution should be implemented and after a certain period of time, it should be reviewed to check whether the change was successful or not. The generic engineering change process can be divided into three main stages as shown in the Figure 5. Communication is the key factor required between different domains within the company in engineering change process depending upon how far the product is in the life cycle. Engineering change propagation procedure can maintain consistency by propagating ECs in a base product definition to product data views [65].



Figure 5: Generic engineering change processes [64]

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

10. Methods and Tools to support ECM

An extensive list of tools and methods has been proposed by the researchers to support the firms to manage the engineering changes in the products effectively and efficiently. Complete list of 54 ECM methods and their existence also documented by methodical literature survey [15]. Most of them are based on design structure matrix (DSM) [15, 66]. The products are decomposed into components and each component further classified by its structural attributes, elements and their inter-relations are linked as shown in figure 6. Components direct dependencies or interrelations are captured in Design structure matrix (DSM) as shown in the Figure 7. This tool also enables user to model, envisage and examine the dependencies among the entities of any system and derive suggestions for the improvement or synthesis of a system. Impact of change propagation through dependency is quantified by estimating the likelihood values by considering the expected frequency of change propagation. The effort to redesign the affected component is indicated by the impact values if change does propagate, as a proportion of that required to design the component originally.



Figure 6: Products with Structural attributes, elements and their inter-relations [15]



Figure 7: Design Structure Matrix [15]

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

11. Version control in ECM

Items in Configuration management evolve through a formal revision. Design variation, change to a document's content or a modification to a part such that part remains interchangeable with its previous variation is said to be "Revision". Item revisions typically identify distinct steps in the evolution of an item. Versions often are not sequential and commonly used to identify a specific set of features and/or a particular build number.

A key aspect in engineering change processes is to manage and control the different documents (e.g. design documents, 3D CAD models, attributes, drawings and technical specifications) as shown in figure 8. Once the design freeze happens, all the related design documents, data's etc. is stored in archives. When changes happen to any document or file in the stored database, a new document version i.e. building block is created. The change initiator or change owner who is responsible for the changes, are to create a new engineering change with description and reason for change are assigned and linked to the created building block.

PLM systems offer different potential regarding the visibility of building blocks and documents and set them in such a way that only the last versions are visible. Access to old versions is possible via links between building blocks and documents.



Figure 8: Versioning scheme in PLM platform

12. Information system

The information system builds the necessary infrastructure for effective ECM. Changes are unavoidable, and should not be neglected in information system development and implementation projects. The PLM system has enough matured to provide orderly information system which fulfills the requirements of development and orderly production (figure 9). PLM systems support Information management by defining steps related to the development, distribution, use of product data and release mechanism or promotion levels that the data must achieve. The systematic manner in which the approach to be followed will varies with every PLM system. The current approach / Work Flow mechanism is defined in a company's configuration management or engineering change procedures and in its new product development process, often changes have to be made to take advantage of the communication and coordination capabilities of the PLM system. It is a fact the above way of electronic communications have their own limitations and it is very convenient for informing the team members, but it cannot replace a formal discussions or creative dialogue within the team. Engineering Change approval requires an intense communication via video conferencing.

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021



Figure 9: Information Management in ECM

13. Workflow Management in ECM

Engineering changes in design is unavoidable and iterative which involves design documents, 3D CAD models, attributes, drawings and technical specifications often circulate among design groups, DMU, planning, manufacturing, tooling, Quality assurance, shops etc. The way to connect these groups together to get feedback, co-ordination and correction incorporation to avoid costly changes during development stage is by means of 'Work Flow processes' as shown in figure 9. The effective way of implementing the 'Work Flow' is through PLM system, which is having a methodology to connect this iterative work and feedback/discussions among various groups within a team in order to introduce changes and provide them with the necessary information. The PLM system of workflow management controls the information flow among different teams according to a sequence defined by the industry or firms 'Work Flow' by top level management as shown in figure 10. The routine activities have been mechanized in electronic form in order to allow their transfer within a computer network.

The following steps to be followed in Workflow Management in PLM system:

- Defining and modelling the workflows according to Industry scope, i.e., defining the sequence of activities, volume and type of data to be handled, data's to be storage and retrieval etc. and describing those aspects of a process that are relevant to controlling and coordinating the execution of its tasks
- Providing for design and implementation of the processes or information flow as business needs and information systems change

Effectively support of Work Flow management in CAD/PLM environment requires:

- Integration and interoperability corresponding to varied, independent, and/or distributed legacy and new systems
- Maintain the workflow applications corresponding to business or information process implementations
- Guarantee the correctness and reliability of applications in the presence of concurrency and failures
- Sustain the evolution, replacement, and addition of workflow applications
- Setting-up the authority or right access for users and those in charge of approvals
- Smooth data or information flow work by setting up the necessary software and network connections

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021



Figure 10: Work Flow Process

14. System Modelling & Language support for ECM

A decision based approach by integrating the engineering concepts into a programmable language for computational assistance in developing system specifications to overcome document-based approaches. System models can be build by using modelling languages which has inbuilt knowledge based approach for making decisions in computer manageable ways [67]. Modelling capabilities for engineering change includes (a) Change models which enable producers and users of specifications to easily find out how new specifications changed and effect on their tasks (b) Management of changes in requests, orders, and their urgency & impact (c) Change processes & order effectivity. Most widely used language for model building is SysML/UML, is an open standard language developed by the Object Management Group (OMG), initiated by the International Council on Systems Engineering. These languages adopted by all commercial and open source systems engineering modelling tools.

15. Summary Records of Discussion

In this paper, we discussed about the elements of 'Engineering changes', such as its categorization, characteristics, process, methods and tools used, system modelling techniques, versioning, workflow management, information management during product design process. Also discussed and compared Configuration Management with Change management and its significance in the product development process during product lifecycle stage.

The goal of engineering change is to enhance the redesigned products performance and to be produced effectively. If Engineering changes (EC) in the product are not managed properly throughout the product lifecycle, it will result in a severe loss. Change propagation causes large delays and unexpected spending. Engineering changes are necessary to improve the product's quality and are the source for innovation.

It has been elaborated about how to manage engineering changes effectively; it is paramount to understand the impact, likelihood and propagation path of engineering changes. Knowledge from previous design change cases is an important asset for companies. Many design conflicts arising from change analysis can be handled by reusing well-formalized way of knowledge, which abstracted from the previous design cases.

It is evident from the research review presented here that the amount of research carried out in the field of ECM has significantly increased during the last two decades. Extensive academic efforts are required to develop tools and manage knowledge to facilitate firms to enhance their engineering change processes.

References

Otto K and Wood K 2001 Product Design: Techniques in Reverse Engineering, *Systematic Design, and New Product Development*, New York, USA: Prentice-Hall.

Huang G Q, Yee W Y and Mak K L 2003 Current Practice of Engineering Change Management in Hong Kong Manufacturing Industries, *Journal of Materials Processing Technology* Vol. 139 No. (1–3), p. 481-487. Eckert C, Clarkson P J and Zanker W 2004 Change and Customisation in Complex Engineering Domains

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

Res Eng Des Vol. 15 No. 1, p. 1-21

Balogun J and Jenkins M 2003 Re-Conceiving Change Management: A Knowledge-Based Perspective *European Management Journal* Vol. 21 No. 2, p. 247-257

McIntosh K G 1995 Engineering Data Management: A Guide to Successful Implementation, New York:McGraw-Hill. http://www.prosci.com/main/change_history.html

Donald N Frank 2003 Configuration Management in Aerospace and Defence, D N Frank Associates, Florham Park, NJ

http://www.ptc.com/WCMS/files/43552/en/CCM-2067-v4.pdf

http://www.aia-aerospace.org/assets/aerospace_standardization0105.pdf

http://en.wikipedia.org/wiki/Configuration_management.

Glenn Hass January 2003 Configuration Management Principles and Practice, Addison-Wesley Longman Publishing Co., Inc. Boston, MA, USA

http://www.laccei.org/LACCEI2009-Venezuela/Papers/ED089_CalvoNarvaez.pdf

MIL-HDBK-61A 2001 Configuration Management Guidance

Glenn Hass 2003 Configuration Management Principles and Practice, Addison-Wesley Longman Publishing Co., Inc. Boston, MA, USA

Bahram Hamraz, Nicholas H M Caldwell, David C Wynn and P John Clarkson 2013 Requirements-based development of an improved engineering change management method, *Journal of Engineering Design*, 24:11, 765-793, DOI: 10.1080/09544828.2013.834039

Colin Bainbridge 1996 Business Re-engineering and Change Management, Wiley, John & Sons Inc.,

http://en.wikipedia.org/wiki/Change_management

Wright I C 1999 A Review of Research into Engineering Change Management: Implication for ProductDesign, *Design Studies* Vol. 18, p. 33-42

Hamraz B, Caldwell N H M and Clarkson P J 2013 A Holistic Categorization Framework for Literature on Engineering Change Management *System Eng.* Vol. 16, No. 4, p. 473-505

William F Rowell, Alex H B Duffy and Iain M Boyle, et al. 2009 The Nature of Engineering Change in aComplex Product Development Cycle 7th Annual Conference on Systems Engineering Research,

Loughborough University

Diprima M 1982 Engineering Change Control and Implementation Considerations *Production and Inventory Management*, Vol. 23, p. 81-87

Lindermann, Reichwald 1998 Integriertes Anderungsmanamement Springer, Berlin

Huang G Q, Yee W Y and Mak K L 2003 Current Practices of Engineering Change Management in Hong Kong Manufacturing Industries *Journal of Materials Processing Technology*. Vol. 139, p. 481-487

Fricke E, Gebhard B, Negele H, et al. 2000 Coping with Changes: Causes Findings and Strategies.

Systems Engineering Vol. 3, No. 4, p. 169-179

Ahmed S and Kanike Y 2007 Engineering Change during a Product's Lifecycle International Conference on Engineering Design (ICED'07) Paris, France

Change Management Procedure 2013 SKA-TEL.SE.CONF-SKO-PR-001

Jarratt T, Clarkson P J and Eckert C M 2005 Engineering change. Design Process Improvement: A review of current practice, Springer London, UK, p. 262-285

Coate G, Duffy A and Whitfield I 2004 Engineering management: operational design coordination J. Eng.

Design. Vol. 15, p. 433-477

H Wildemann 1994 Änderungsmanagement-Leitfaden zur Einführung eines effizienten Managements technischer Änderungen TCW, München

M Gemmerich 1996 Zeitorientiertes Management technischer Änderungen, Technol Manage Vol. 3, No.45

Monica Giffin, Olivier de Weck and Gergana Bounova 2009 Change Propagation Analysis in Complex Technical Systems *Journal of Mechanical Design* Vol. 131

Edwin C Y Koh, Nicholas H M Caldwell and P John Clarkson 2012 A Method to Assess the Effects of Engineering Change Propagation *Res Eng Design* Vol. 23, p. 329-351

Martin M V and Ishii K 2002 Design for Variety: Developing Standardized and Modularized Product Platform Architectures *Res Eng Des* Vol. 13, p. 213-235

Fricke E and Schulz A P 2005 Design for Changeability (DFC): Principles to Enable Changes in Systemsthroughout their Entire Lifecycle *Syst Eng* Vol. 8, p. 342-359

Ho C J and Li J 1997 Progressive Engineering Changes in Multi-Level Product Structures *Omega Int JManag Sci* Vol. 25, p. 585-594

Cohen T, Navathe S B and Fulton R E 2000 C-FAR, Change Favourable Representation *ComputerAided Design* Vol. 32, p. 321-338

https://community.plm.automation.siemens.com/t5/Teamcenter-Blog/Product-Architecture-Breakdown-Guides-Product-Engineering/ba-p/306102

David F Wyatt, David C Wynn and P John Clarkson 2009 A Computational Method to Support Product Architecture Design ASME International Mechanical Engineering Congress and Exposition, Florida,

ISSN- 2394-5125 VOL 08, ISSUE 05, 2021

USA, p. 13-19

Karl Ulrich 1995 The Role of Product Architecture in the Manufacturing Firm *Research Policy* Vol. 24No. 3, p. 419-440 Yassine A A and Wissmann L A 2007 The Implications of Product Architecture on the Firm *SystemsEngineering* Vol. 10 No. 2, p. 118-137.

Eric Bonjour, Ghassen Harmel and Jean Pierre Micaëlli 2011 Simulating Change Propagation between Product Architecture and Development Organization, *International Journal of Mass Customisation*, Inderscience Vol. 3, No. 3, p. 288-310

Browning T R 2001 Applying the Design Structure Matrix to System Decomposition and IntegrationProblems: A Review and New Directions *IEEE Trans. Eng. Mgt* Vol. 48, No. 3, p. 292-306

T Jarratt, C Eckert and P J Clarkson 2002 Product Architecture and the Propagation of Engineering Change International Design Conference, Dubrovnik

Sosa M E, Eppinger S D and Rowles C M 2000 Designing Modular and Integrative Systems *Proceedings of DETC '00:* ASME 2000 International Design Engineering Technical Conferences

Michael Egan 2004 Implementing a Successful Modular Design, 7th workshop on Product Structuring -

Product platform Development, Chalmers University of Technology, Goteborg

Kaushik Sinha and Olivier L de Weck 2013 Structural Complexity Quantification for Engineered Complex Systems and Implications on System Architecture and Design *International Design Engineering Technical Conferences*, Portland, Oregon, USA

Ulrich K T and Seering W P 1990 Functional Sharing in Mechanical Design, *Design Studies* Vol. 11No.4, p. 223-234 Whitfield R I, Smith J S and Duffy A H B 2002 Identifying Component Modules *In Proceedings of Seventh International Conference on Artificial Intelligence in Design*, Cambridge, UK, p. 571-592.

Ericsson, Anna and Erixon et al 1999 Controlling Design Variants: Modular Product Platforms *ASME press ISBN 0-87263-514-7*, New York, USA, p. 145.

Stone and Robert B 2000 A Heuristic Method for Identifying Modules for Product Architectures *Design Studies* Vol. 21, p. 5-31

Eric Bonjour, Maryvonne Dulmet and Samuel Deniaud et al. 2009 Propagating Product Architecture Decisions onto the Project Organization: A Comparison Between two Methods *International Journal of Design Engineering* Vol. 2, No. 4, p. 451-471

Ding-Bang Luh, Yao-Tsung Ko and Chia-Hsiang Ma 2011 A Structural Matrix-Based Modelling for Designing Product Variety *Journal of Engineering Design* Vol. 22, No. 1, p. 1-29

S Davis 1989 From Future Perfect: Mass Customization Planning Review, Vol. 17, No. 2, p.16-21

J Ping, B Victor and A Boyton 1993 Making Mass Customization Work *Harvard Business Review* Vol.71,No. 5, p.108-111

Otto K 2001 A Process of Modularizing Product Families *Proceedings International Conference on Engineering Design, Design Management*, Glasgow, UK, p. 523-530

Erens F 1996 The Synthesis of Variety, Dissertation, Eindhoven University of Technology

Simpson T W 2004 Product Platform Design and Customization: Status and Promise Artificial Intelligence for Engineering Design, Analysis and Manufacturing Vol. 18, p. 3-20.

Clarkson P J, Simons C and Eckert C 2004 Predicting Change Propagation in Complex Design *J MechDes* Vol. 126, No. 5, p. 788-797.

Williams O J 1983 Change Control in the Job Shop Environment *Proceedings of the 26th Annual International Conference of the American Production and Inventory Control Society*, Toronto, Canada, p. 496-498.

Prabhu Shankar, Beshoy Morkos and Joshua D Summers 2012 Reasons for Change Propagation: A Case Study in an Automotive OEM *Res Eng Design* DOI 10.1007/s00163-012-0132-2

Edwin CY Koh, P John Clarkson 2009 A Modelling Method to Manage Change Propagation

International Conference on Engineering Design, ICED'09, STANFORD, USA.

Eckert C, Zanker W and Clarkson P J 2001 Aspects of a Better Understanding of Changes International Conference on Engineering Design, ICED'01, Glasgow, UK.

Beshoy Morkos, Prabhu Shankar and Joshua D Summers 2012 Predicting Requirement Change Propagation, Using Higher Order Design Structure Matrices: An Industry Case Study *Journal of Engineering Design*. Vol. 23, No. 12, p. 905-926.

Jarratt T, Eckert C and Clarkson P J 2006 Pitfalls of engineering change: change practice during complex product design, *Springer Series in Advanced Manufacturing*, London, pp. 413–423.

N Do, I J Choi and M Song 2008 Propagation of Engineering Changes to Multiple Product Data Views Using History of Product Structure Changes International Journal of Computer Integrated Manufacturing Vol. 21, No. 1, p. 19-32.

D C Wynn, N H M Caldwell and P J Clarkson 2010 Can Change Prediction Help Prioritise Redesign Work in Future Engineering Systems International *Design Conference -Dubrovnik - Croatia*

Conrad Bock and Allison Barnard Feeney 2013, Engineering Change Management Concepts for Systems Modelling, *NISTIR* 7922, http://dx.doi.org/10.6028/NIST.IR.7922