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Engineering product and process design changes: A literature overview

Inayat Ullah[a], Dunbing Tang[a*], Leilei Yin[a]

[a]*College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*

* Corresponding author. Tel.: +86(0)25 84892051; fax: +86(0)25 84891501. *E-mail address:* d.tang@nuaa.edu.cn

Abstract

Engineering product/process design changes are unavoidable and necessary for improvement & innovation. To capture the maximum market shares, manufacturers have to effectively and efficiently manage engineering changes throughout the entire product life. In this paper a comprehensive literature review on engineering change management in product/process perspective is presented. Engineering design changes can be taken in both aspects, such as an opportunity or as a burden. Different methods have been proposed by the researchers for better understanding of engineering change phenomenon. The insight regarding the changes propagation during the engineering design is crucial because a large number of artifacts are results of the predecessors. This article discusses the significant aspects of engineering changes, product architecture, propagation paths and highlighted the methods and tools that are proposed by the researchers. This paper will help researchers and managerial staff to get an idea and awareness about the change propagation and its impact. The review shows the prominence of engineering change management and concluded that the interest in the research field is escalating gradually.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Engineering change; Product life cycle; Design structure matrix; Change propagation; Impact analysis;

1. Introduction

Engineering design change is one of the most influential factor for product innovation. In recent years, engineering change and its management has gained popularity in academic research and as well as in industry. First literature review on engineering change was published in 1997 by Wright [1]. He reviewed literature between 1980-1995 and found few publications on this topic. Due to its popularity overtime, different literature reviews have been conducted by the researchers [2,3]. Most recent literature review has been conducted by Hamraz et al. [3], which reviewed the literature published till September 2011. One of the main purpose of this article is to give an overview of engineering product / process design change management. In this paper, publications after September 2011, are reviewed.

Increasing competitiveness in the market due to fast growing change environment, forces the industrialists to pursuit ways to manufacture a high quality product at a minimal cost with least possible time. To reduce the risk, manufacturing cost and time, companies have promoted focus on the incremental products. Thus, the aim of the designers is to change as little as possible. Most of the new designs are refined versions of the existing designs developed through alterations and changes to the current design [4]. These products have new characteristics, functions and performances that depends on the current product design. To satisfy the customer's requirements, these products are usually available in different kinds, which can require considerable changes to the initial design. Consumers are anxious about the product trustworthiness and thus they are hesitant to use too many unverified components [5]. The information regarding product parameters increases in quantity and also in quality as the design proceeds and provides a better insight of the design issues. In order to avoid undesired change propagation, designers may restrict propagation by freezing product components or their interfaces. Freezing the component design in early stage can restrain novelty, product improvement. On the other hand unfreezing the product elements can trigger the design iterations and increase the cost of redesign. In such cases the optimal freeze order has to be determined.

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The phrase “do it right the first time” is far from reality and very difficult to be applicable [6]. Engineering design changes have been recognized as unavoidable in the development of complex engineering product [5,7]. Engineering design changes have huge influences on production activities and hence making the activity of product development very pricey and prolong [7]. In the early decades the engineering changes were predominantly seen as a problem. People were reluctant to implement the change management system. From the past few decades it has been seen that industrialist take it as an opportunity and source of innovation and creativity [8]. Engineering design changes can facilitate to perform modification and error elimination in existing products. As a result, the product manufacturing cycle time decreases and manufacturers can launch new products to the market in least possible time. Engineering design changes can be taken into account as a driving force for incremental product improvement as customers are interested in more customized products. Keeping in view the above, knowledge attained from engineering changes is very helpful and useful for the design and development of the product. In the field of manufacturing, today’s markets and consumers demand changes so quickly. Engineering design changes arises frequently for continual improvement of system or artifact.

The methodology to carry out the literature review is given in Section 2. Section 3 describes the definition and categorization of ECs and objective of ECM. In Section 4, product architecture has been elaborated. Section 5 gives an idea about the change propagation. Section 6 discusses the engineering change process. In Section 7, tools and methods to support ECM have been presented. Finally, Section 8 summarizes the paper.

2. Methodology

The research commenced with a rigorous literature review on current engineering change management practices. To conduct the literature review on engineering change management, different journals and conferences were focused for the review process and procedure.

2.1. Literature selection

In order to carry out the review on selected topic, a systematic collection of articles is carried out. It consists of following four phases.

Phase-1: In the first pahse, the literature review conducted by Hamraz et al. [4] is accessed thoroughly. Some of the references mentioned in that article are relevant to other research areas, thus the paper which are related to the core field of engineering change management are selected. This article covers the literature review till September 2011.

Phase-2: In the second phase, collection of publications from October 2011 to August 2015 has been done by consulting multitude of journals and conference proceedings related to engineering change management and design. The main journals which are used as a source for the related papers/articles are: Journal of Engineering Design, Computers in Industry, Computer Aided Design and Applications, Design Studies, IEEE Transaction on Engineering Management, Research in Engineering Design, International Journal of Design Engineering, International Journal of Computer Integrated Manufacturing, Computer and Industrial Engineering, Knowledge Based System, Journal of Computing and Information Science in Engineering, Systems Engineering; Artificial Intelligence for Engineering Design. Conferences proceedings which were included in the literature review are: International Design Conference (IDC), ASME International Design Engineering Technical Conference, International Council of Aeronautical Sciences, CIRP International Conference on Life Cycle Engineering, Conference on System Engineering Research, International Conference on Engineering Design (ICED) and International Design Structure Matrix Conference (IDSM).

This phase started with listing down the publications which include the term “change” in the title, abstract and in keywords. Then the selected articles are thoroughly checked to shortlist the publications regarding engineering product and process design change.

Phase 3: In the third phase, the citation record of the core publications in the field of engineering change management maintained by Scopus were accessed thoroughly and the related publications are shortlisted.

Phase 4: In the fourth phase, an open search for the word “engineering change” was carried out with the help of search engines “Google Scholar”, “Scopus” & “SpringerLink” and the related papers are downloaded.

2.2. Publication’s distribution over year

The final list of publications including journal articles and conference papers selected through the aforementioned approach contains 366 publications. 247 publications out of 366 were selected from the literature review conducted by Hamraz et al. [4]. These articles are related to the core field of engineering change management, published till September 2011. The remaining 119 articles are collected for a period from October 2011 to August 2015 through systematic approach. The publications distribution over year is presented in Figure 1. From this graph it has been concluded that interest in the field of engineering change management steadily increased till 2007 where it get its first peak. From 2008 onwards up to 2012 there is a decrease but still remains at the higher level than the period before 2006. From 2013 onward there is again increase in the number of publications. 182 (49.73%) of the publications are journal articles and 184 (50.27%) are conference papers.

2.3. Citation analysis

To view the relation between the research articles, citation analysis has been carried out. Database maintained by Scopus has been used for this analysis. The most cited paper is written by Eckert et al. [8]. It is also mentioned by Hamraz et

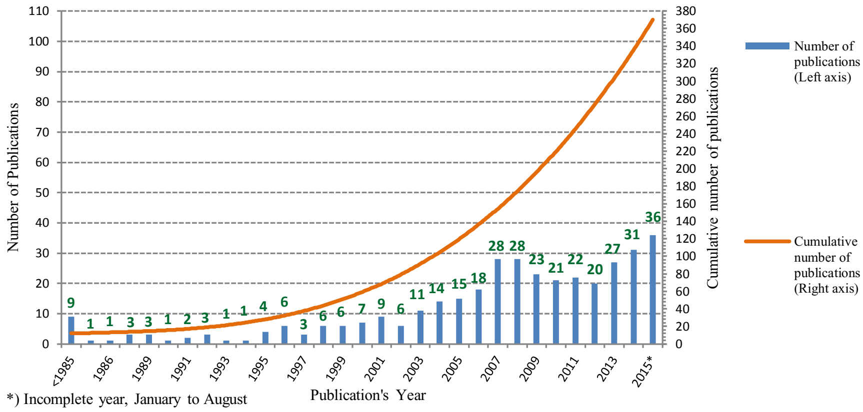

Fig. 1. Publications over year

al. [4] in the literature review. The number of citation of the above mentioned paper in Sep 2011 was 72, recorded by Hamraz et al. [4]. Now the number of citation of the same paper has increased to 257 in Aug 2015. This indicates that there is 358% increase in the number of citations only in 4 years. The second most cited paper is written by Clarkson et al. [9] with 246 numbers of citations. The same paper has 70 numbers of citations in Sep 2011, and also shows an increase of 351%. Huang, G.Q. is most popular researcher in the field of ECM due to its multiple occurrences in the citation database. On the basis of above data we can conclude that the interest in the field of ECM is increasing with a passage of time. The database maintained by Scopus includes approximately 61% (223 of 366) of all the publications. Since 152 out of 223 (68%) are journal articles and 71 out of 223 (32%) are conference papers. Total listed journal articles are 182 out of 366 and 152 journals articles are covered by Scopus database, which is approximately 83.5%. Likewise 184 out of 366, the total listed conference paper and only 71 are covered by Scopus database, which is approximately 38.5%. From the above data it has been concluded that Scopus include more journal articles than the conference papers due to its high impact factor.

3. Engineering change

Engineering design changes are considered as a normal part of the artifact life cycle, therefore it is essential to develop a clear concept regarding engineering design change. Engineering design changes are defined in a different perspective by numerous researchers in the literature. Wright [1] defines the engineering changes as the modification to the component of a product which normally takes place when the product enters the production stage. The definition of Wright [1] limits the engineering changes only to the production phase. Huang & Mak [10] define engineering changes as a modification of components or product associated to forms, fits, materials, dimensions or functions. Huang & Mak [10] defines the scope of the change but not mentioned the time of occurrence. Terwiesch & Loch [11] explained the engineering changes as “Engineering change orders - changes to parts, drawings or software that have already been released”. The drawback of this definition is the unification of change and change order. Jarratt et al. [12] defined the engineering change by considering the size, type, scope and time. Jarratt et al. [12] described engineering change as “an alteration made to parts, drawings or software that has already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time.”

Hamraz et al. [4] defined engineering change as “changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behaviour (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behaviour (design principles), or behaviour and structure (physical laws) of a technical artifact”. Engineering changes can cause disorder into a previously stable operation by changing elements swiftly and severely. As a result the modifications are considered as distracting to the well-established processes. Engineering changes are categorized into three different classes, named as convenient, mandatory and immediate which represents different degree of importance for engineering change implementation. Engineering change management consumes 30% to 50%, sometime upto 70% of the production capacity. It represents 20% to 50% of manufacturing tool cost [7]. Some other reports suggest that engineering changes usually consumes approximately one third of the engineering design capacity [13]. The key to the success is the right formulation of the problem and to find the solutions to those problems by changing as little as possible.

3.1. Engineering change management

According to Jarratt et al. [12] “engineering change management refers to the organization and control of the process of making alterations to products”. Efficient ECM can ensure that current version of documentation regarding process and product data are available at desired place. Engineering change management depends upon the engineering processes, management, engineering and information technologies. Engineering change management practices intended to divide the design process into manageable stages and ensure the quality at each stage. The objective of engineering change management is to minimize the occurrence of changes and if changes occur then handle these changes in a proper way to reduce the loss in terms of cost, time and quality. For the better management of changes, Fricke et al. [14] gives five attributes: Less, Earlier, Effective, Efficient and Better.

Organisational structure and size of a firm can influence how a product design change is executed. Many firms have implemented EC procedures to control the impact of engineering design changes. EC needs to be approved by a project manager or a change committee, depending on the size of the proposed change and the size of the organisation. It is observed that in some firms the signature loop required for authorisation involved more than 20 people. Large signature loops will require many days to approve and implement an EC. Communication between multidisciplinary teams plays an important role in the success of product development. It is revealed from the literature that up to two-thirds of all engineering changes could be prevented by better communication and discipline. Concept of concurrent engineering, promotes improved communication. ECM looks a rather simple activity for organizations producing small products, but it gets more complex in industries such as aeronautics or automotive industry where the whole supply chain can be impacted [15]. Each engineering change involves cost. Engineering change cost in each consecutive stage is being ten times more than the earlier stage within the product life cycle [16]. In manufacturing, handling changes usually absorb from 20% to 50% of the product development capacity. On the other side, evidence from empirical investigations [5] show that 70-80% of entire product cost is decided during early design stages.

3.2. The categorization of engineering changes

Multiple studies have been conducted to evaluate the nature and importance of engineering changes. Researchers categorize changes by distinguishing them into a problem or innovation. Eckert et al. [8] extended that categorization by considering the origin of the change. The reason for making engineering changes, can arise from different sources such as change in the part application, replacement or withdrawal of a part, errors rectification, changes in the customer requirement, new legislation, supplier constraints, complications in components manufacturing or assembly, prototype testing, quality issues, etc. [17]. The aim of making changes to the products can be performance improvement, error correction, technological changes, etc. Engineering changes can be mainly categorized into two subclasses, as emergent changes and initiated changes.

Emergent change: These are the changes arises from the product itself due to the error during the design process. These changes are also termed as unintended changes and occur when some features of the system design needs changing because of errors or miscalculations [18]. The reasons of emergent changes are error rectification and safety etc.

Initiated change: These are the changes originating or arising from the external source. Initiated changes are those advised by the shareholder. In this perspective, innovation is considered as a part of initiated changes for product improvement [8]. The reasons of initiated changes are customer, legislation, production, cost reduction, performance, maintainability, technological progress and durability/life etc.

4. Product architecture

Product is a combination of several components or sub-systems. Product architecture is the arrangement of the parts by which the product's function is assigned to the physical components. It is fact that the product architecture has a significant impact on the product success. The product architecture is described as the configuration of the product functional elements into numerous physical building blocks, including the lay out of the functional element to physical components [19]. Product architecture can affect the product change, product variety, component standardization, product performance and product development management. The main aspect of the product architecture is the degree to which it is modular or integral [20]. There are 3 different scenarios for mapping of functional elements to physical components: one to one, one to many and many to one.

4.1. Product classification

According to Jarratt et al. [3] the change impact on a product has been influenced by three elements: *(1)* product architecture *(2)* product complexity *(3)* degree of innovation within the product. Products can be categorized into main two classes based on their architecture.

Complex Product: It is essential to establish an idea about complexity because product complexity is conceptualized in many ways. There are numerous opinions regarding complexity which were brought together by Eckert et al. [21] in the perspective of engineering change. The main class of complexity from a viewpoint of engineering change is connectivity. Numerous researchers describe the measure of complexity as the connections between components and their interaction inside a system. An integral architecture consists of a complex mapping from functional elements to physical components and/or coupled interfaces between the components. The complexity of technical systems relies on the diversity and number of distinct elements and their connectivity arrangement. In the integral architecture every physical components accomplish more than one functional element and it is known as a function sharing.

Modular products: Modules can be defined as the physical structure which has one-to-one relation with the functional structure. They are considered simply as a building block with distinct interfaces. Modular products may be described as assemblies, machines, or components that achieve an overall function through coalition of different building blocks or modules [22]. A module is a product block whose structural components are strongly linked among themselves and

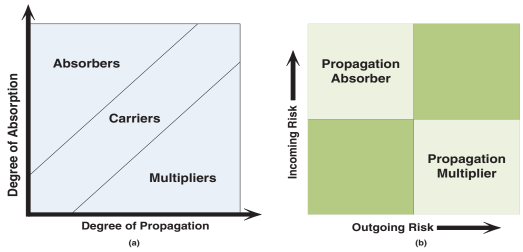

Fig. 2. (a) Components change propagation characteristics [8]; (b) Component classification based on change risk [5]

comparatively weakly linked to the other unit components. So a change in a module's component has the great probability to cause changes in components within the same module. Modules are presumed to be functionally self-reliant or have slightest connections. A change in a module can propagate to the other modules because interfaces and linking parameters exist between them. A change to one module can be made without changing the other modules if the interfaces remain unchanged.

4.2. Components / sub-systems classification

The components or sub-systems of the product are interlinked with each-other. During the study by Eckert et al. [8], identify four types of change propagation behaviours named as multiplier, absorber, carrier and constant. These four types of change propagations represent four different situations. When the change is initiated by one component and it propagates to the other components through linkages between them, so different components behaves in a different ways. These classifications are illustrated in Figure 2.

Multiplier: Multiplier is a component that inflates the change problem and makes the situation worst. These components can instigate an "avalanche" of changes [8,13] or referred as the snowball effect [11]. Such changes have major effect on the budget, product lead time and the organization.

Absorber: An absorber eradicates or absorbs all the changes. If the number of input change is more than the number of output changes then it would be partial absorber. But if the numbers of output changes are zero then it would be complete absorber and thus accommodating all the changes. The later situation is uncommon. Absorbers alleviate the complexity of the change propagation.

Carrier: A carrier can be defined as component that neither add nor reduce the number of changes. It means that the input to that component is equal to the output. They replace the changes with the new one from the intermediate component [23].

Constant: This component remains unchanged and the change is being passed without any effect [8,23]. They just transfer the change from one component to the other components by which they are interlinked.

5. Change propagation

Change propagation is a phenomenon by which one change triggers a sequence of others changes and can potentially

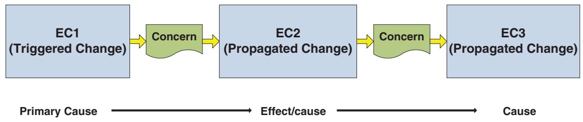

Fig. 3. Representation of change propagation [25]

distract the manufacturing process [24]. Change propagation can be considered as the cause-effect, cause-effect pattern [25]. Change propagation is an issue that affects both the product and the organization. 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 3. The EC1 is the primary cause for the EC2 and triggers a sequence of other changes.

In the products, parts are interconnected through the parameters such as spatial, geometry, material, function and behaviour. Therefore changing in anyone of these parameters may initiate changes in the numerous other parameters of the system [8]. Second-order change propagations are most likely to propagate and are difficult to foresee at the time of change. 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. Change propagation affects many aspects of the product design and requires much rework to implement.

5.1. Change propagation paths

If one part changes, this change may have knock-on effects on associated parts, thus there exists a possibility that nearby parts may change in response. These parts can then in turn cause further changes to neighboring parts, so that changes spread all over the system/artifact. From different studies it has been observed that change can propagate to the direct and indirect linking parameters between the components of the system. It means that changes can affect other department in the organization which is not directly concerned with these changes. For instance, changing in the size of the artifact can lead to the change in the dimensions of the packing box, changing the product material can affect the cutting tool during manufacturing. Thus, change propagation phenomenon is not limited to the physical interconnection of the system components but also due to the parameters connecting different departments within the firm. In an artifact different types of links can be defined between the components. Interface link defines the closeness of two components within the system and can be specified by positioning, geometry and assembly process. Dimensioning link defines that change in the dimension of one component. With the help of association link it is possible to detect all the physical components impacted by the change in system's function. In complex products the parts or sub-systems are closely dependent and are associated through the connecting parameters such as material, geometry, behaviour and function. Thus changes in one part of the system have the high likelihood to propagate to the other parts of the system. Propagation paths can lead to unexpected changes and also highlights the components for designers where knock-on changes have to be refrained [5].

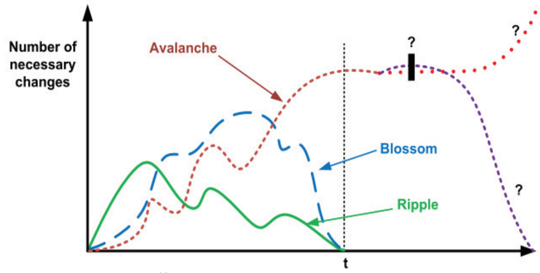

Fig. 4. Different patterns of change propagation [8]

5.2. Change propagation impact, risk and analysis

Numerous methods have been proposed by the researchers to simulate and analyze the propagation of changes in an artifact, so that the time, cost and resources can be allocated according to the impact of the change. Changes can have different origins and nature, and often not all the consequences of the changes are expected or desired. When a change is worked out in detail then it is possible to know which other parts or sub-systems of the artifact to be affected by the change under consideration. In a cross-domain approach, design is decomposes and identify possible change propagation linkages to assess change impact. Cross-domain modeling approach help to analyze a design to create and capture the information required for change prediction [26]. When a design projects moves to maturity phase, most of the design parts are frozen, as they cannot be changed for logistical or other reasons. So it means that later changes are more constrained than former changes.

Changes can be instigated in the product design if the artifact cannot deliver the desired performance. To evaluate and handle change propagation, various techniques have been reviewed. These techniques focus on different information domains such as component, requirement, function, parameter design process & event and change propagation concepts on which they are based. When the impact of engineering changes is investigated, then it is important to identify the actors involved in the change. It is necessary to limit the changes in the product design when it is closed to the decision milestone. Change propagation analysis is necessary to predict and simulate the impact of changes inorder to improve the capacity to manage time, cost, resources and quality. These analysis procedures rely on the human communication, knowledge and experience of the individuals, common sense and configuration management [27].

5.3. Change propagation classification

Changes can propagate, thus affecting numerous parts of the product. In case of product family, the changes can also affect the other products having common platform. Two different types of change propagation have been identified by Eckert et al. [8], ending change propagation and unending change propagation.

Ending change propagation can be classified as ripple and

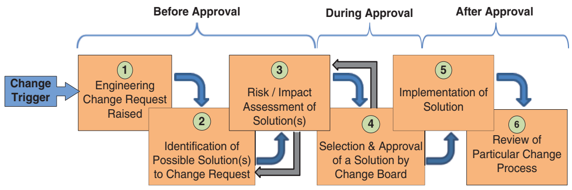

Fig. 5. Generic engineering change process [12]

blossom. In case of ripple the numbers of changes are less in volume and are put under control quickly, thus decreasing rapidly because of the absorbers. These types of changes have low risk and can be settled down within stipulated time frame and cost. Blossoms are those changes which are high in numbers. They are increasing with the passage of time but can be brought to conclusion within the projected time frame as shown in Figure 4. The increase in the volume is because of multipliers and that type of changes can be placed in the category of medium risk. They consume more resources as compared to ripple.

Unending change causes numerous other considerable changes and cannot be brought under control so that phenomenon is known as the change avalanche. These changes are continuously increasing with the passage of time as shown in Figure 4. The propagating change passes through several change multipliers, spreading to more and more components. A change avalanche can be disastrous for a project, causing cost and project schedule overruns. The same phenomenon is also referred as "snowball effect" by Terwiesch & Loch [11]. These types of changes can be put in the category of high risk. Sometimes it might not be possible to conclude the project within approved budget, so the project has to be terminated to avoid the further loss.

6. Engineering change process

Engineering change process is an essential process of the configuration management. In order to control the consequences of engineering changes many companies have adopted the formal engineering change procedure as shown in Figure 5. Six phase generic engineering change process gets it initiation from the so called change trigger. In such practices, if the change trigger is found to be significant, a well-founded change request can be raised by the firm's employee or by the external source. The change request must encompass the reasoning, priority, type and the components to be affected. Then the potential solutions to the engineering change request should be identified. Impact & risk assessment should be carried out to prioritize the possible solutions. In this phase the impact on the cost and the project schedule is also highlighted. 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. It is obvious that later the engineering changes occur in the design process; more significant will be the impact. It is then circulated to the effected departments for their reservations

Table 1. ECM Methods and Tools

No.	Tool / Method Name	Purpose / Description	Authors & Publication year	Journal/Conference
1	Integrated ECM process model	This model captures the changes in design and share events for handling changes done by shareholder.	Han, Lee and Nyamsuren 2015	Int J Comput Integr Manuf
2	Tree-Root tracking and ripple strategy method	It evaluates the impact range of Engineering Changes which help to identify that how to rearrange the schedule and to optimize the Engineering Change execution after manufacturing starts.	Leng et al. 2015	Int J Adv Manuf Technol
3	Change propagation algorithm	It predicts change propagation from aircraft elements to assembly tooling and a computer-aided system is developed to assist the designers in predicting change propagation.	Tang and Yin 2015	6th IACIEMI
4	Engineering change forecast	In this method EC forecast are used to point out and arrange product parts for modularisation.	Koh et al. 2015	Res Eng Des
5	An attribute-based and object-oriented approach	This approach models the integrated content of a product by characterizing its components and associated requirements with attributes & linkages and performs change impact analysis.	Chen, Liao and Lin 2015	Comput-Aided Des
6	Dynamic Bayesian network	It is a model-driven methodology to optimize freeze sequence recognition which is based on risk of change propagation.	Lee and Hong 2015	Ind Manag Data Syst
7	Activity network-based process model	This model explores that which design activities need to be targeted to prevent and react to critical iteration-likelihood changes.	Daniel et al. 2015	Concurr Eng (research and applications)
8	Big data analytics method	This method evaluates the external and internal uncertainties in product design and can also identify the most affected product components under uncertainty.	Afshari and Peng 2015	Ind Manag Data Syst
9	Simulation Based Method	It assesses the isolated upshot of product design on product evolvability by analysing DSM.	Luo 2015	Res Eng Des
10	Design workflows simulation model	The model foresees schedule risk and resource requirements of a change process, considering concurrency, iterations during redesign and multiple change sources.	Wynn, Caldwell and Clarkson 2014	J Mech Des
11	SysML based methodology	It evaluates change situations that arise during the production systems development to support the assessment of possible effects of engineering changes on the system and also on the future phases of production system.	Kernschmidt et al. 2014	47th CIRP Conf Manuf Syst
12	Data model	It facilitates the access to necessary information about relations or dependencies between requirement, solution or production artefacts.	Chucholowski et al. 2014	13th IDC
13	Change propagation analysis method	To support the designers to identify changes efficiently, This method explores change propagation analysis from aircraft to assembly tooling.	Yin et al. 2014	J Eng Manuf
14	FBS Linkage method	It is change propagation model of multi-domain, based on the idea of CPM and the functional reasoning.	Bahram et al. 2014	Res Eng Des
15	Attribute based, object oriented approach	This approach models the integrated content of a product by characterizing its components and associated requirements with attributes and linkages.	Chen, Liao and Lin 2014	Comput-Aided Des
16	DSS methodology	It helps to comprehend the risk and cost of change.	Zhao et al. 2014	Comput Ind Eng
17	VV&T Implementation tool	Validation, verification and testing tool assist in mitigating the negative effects of engineering change propagation and help to minimize the opportunities for human error.	Phelan, Summers and Guarneri 2014	TMCE
18	Matrix based modelling method	Enhance the traceability of design changes occurring between functional and structural domains.	Fei et al. 2013	Comput-Aided Des Appl
19	Knowledge based approach	It determines significant engineering change features that should be compared to recover similar past engineering changes so that the impact of proposed EC outcome can be assessed.	Mehta, Patil and Dutta 2013	ASME Trans J Mech Des
20	Dependency modelling technique	This modelling technique support companies in assessing the changeability of complex engineering systems.	Koh, Caldwell and Clarkson 2013	J Eng Des
21	Dependency-based change propagation approach	This tool is capable to deal with engineering changes extended to product families and is based on a multilevel representation of the product structure.	Raffaeli et al. 2013	ASME DETC
22	Matrix-calculation-based algorithm	It is useful to analyze change propagation in a numerical product model and also to support change prediction.	Hamraz, Caldwell and Clarkson 2013	IEEE Trans Eng Manag
23	Ontology-based retrieving method	It is an effective approach to achieve solutions for new changes by retrieving and reusing existing cases.	Wang and Wan 2013	19th ICAC
24.	Requirement modelling tool	It provides insight into the requirements which may be affected before approving an EC using higher order DSM.	Morkos, Shankar and Summers 2012	J Eng Des
25.	Multidomain engineering change propagation model	This model combines concepts of both the function-behaviour-structure model from Gero with the change prediction method (CPM) from Clarkson.	Hamraz, Caldwell and Clarkson 2012	ASEM Trans J Mech Des
26.	Modelling method	It supports the prediction and management of undesired engineering change propagation during the complex products design and development.	Koh, Caldwell and Clarkson 2012	Res Eng Des
27.	Multilayer network model	This model integrates three coupled layers of product development.	Pasqual and de Weck 2012	Res Eng Des
28.	System dynamics model	It investigates the relations between new product development and engineering change management processes.	Reddi and Moon 2012	Ind Manag Data Syst

No.	Tool / Method Name	Purpose / Description	Authors & Publication year	Journal/Conference
29.	Information-based approach	This approach work out the similitude between engineering changes, each described by a set of dissimilar attributes.	Mehta, Patil and Dutta 2012	IEEE Trans Auto Sci Eng
30.	Design change analysis method	It helps designers to trace, analyse and assess engineering changes occurring in the product design phase.	Fei et al. 2011	Int J Comput Integr Manuf
31.	Simulation model	This simulation model is used to investigate the mutual impacts of ECM process and new product development (NPD) process on each other.	Li and Moon 2011	Int J Adv Manuf Technol
32.	Agent-oriented approach	It works by repairing violations of required consistency rules in a design model.	Dam and Winikoff 2011	Auton Agent Multi-Agent Syst

and valuable inputs. The Changes Release Board (CRB) then validates the engineering changes and determines whether it can be approved for implementation.

Finally the approved solution should be sent to the effected parties for the implementation. Depending upon the change nature, the implementation can be immediate or phased over time. The related drawings and other documentations must be updated at that stage and it must be ensured that only the updated documents are available at the designated places. After a certain span of time, it must be assessed to ensure whether the change was successful or not. The generic engineering change process can be divided into three main phases as shown in Figure 5. Some break points are also defined in the engineering change process and the purpose of these break points is to stop the engineering change process if necessary. For instance, at phase 3 if the impact assessment shows that the engineering change is too risky then it should be immediately stopped at that point. The documents which are used to support the engineering change process are named in a several ways depending on the researchers. Some common titles for these documents are Engineering Change Request (ECR), Engineering Change Order (ECO), Engineering Change Proposal (ECP), Engineering/Enterprise Change Notice (ECN) and Engineering change Log (ECL).

7. Tools and methods to support ECM

It is revealed from literature review that the methods and tools proposed by numerous researchers in the field of engineering change management can be broadly classified into two categories. In the first category, engineering design changes are only recorded and reported [28], while in the second category the engineering design changes are modeled and analyzed [29]. To uphold the decision making during the engineering change process, numerous techniques are used by industrialists. These methods and tools support the organizations to manage the engineering changes, effectively and efficiently in products / process design. Most of them are based on Dependency Structure Matrix (DSM). Several techniques and methodologies exist to avoid engineering changes as much as possible, for instance, quality function deployment. Some methods exist to make changes as early as possible in the engineering design process, such as concurrent engineering. Comprehensive list of engineering change management methods and tools through systematic literature review has been provided by Hamraz et al. [30]. The aforementioned literature review was conducted upto Sep 2011. Form Sep 2011 onwards the detailed list of methods and tools for product/process design changes proposed by different researchers is reported in Table 1.

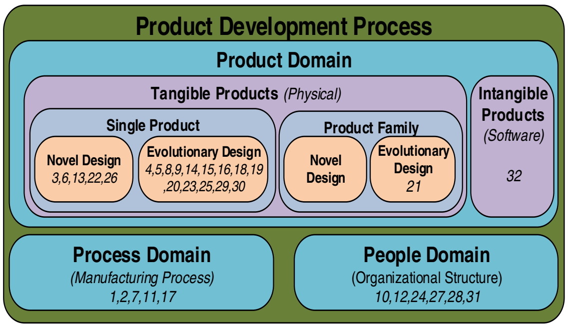

Fig. 6. Application area of tools/methods presented in table 1 (Digits represent the "No" in table 1)

Figure 6 indicates three domains for the product development process: the product, the process and the people domain. The product domain can be divided into tangible and intangible products. It can be further categorized as single product and product family. The engineering methods and tools described in table 1 can be used in different domains as shown in Figure 6. Efficient utilization of above mentioned methods and tools can increase product development capability and quality, reduce development cycle time and cost and ultimately increase product marketability.

8. Summary

Engineering design changes are an indispensable characteristic of the product developments process. The ultimate goal of engineering product/process design change is to enhance the performance of redesign product or to be produced effectively. Engineering design changes in the product can occurred throughout the product entire life, resulting in a serious profit loss if not managed effectively. It is challenging to predict change propagations and their impacts, due to which uncertainty arises in product design. Change propagation causes large delays and unexpected spending. Engineering product/process design changes are necessary to improve the product's quality and are the source for innovation. In recent years various methods and tools on change propagation have been proposed by the researchers. For instance, some methods indicates potential change propagation paths, some calculating the risk for a change to propagate, some methods map physical components whereas other map functional, behavioural and parameter linkages in the product. Some methods are limited to the specific aspects of the product lifecycle and some are applied to all the product development stages. To manage engineering changes effectively it is necessary that it must be set as an organizational goal and its accomplishment must be planned prudently.

It has been revealed from the literature review that to effectively manage engineering product/process design changes, it is paramount to comprehend the impact, likelihood and propagation paths of engineering design changes. Insight from earlier design change problems is a significant resource for companies. Most of the design clashes emerging from change analysis can be dealt by reusing well-formalized and managed knowledge extracted from earlier design issues. Engineering product design change in one part of a complex product arise changes in further parts and even also to the entire product. On the other hand, in modular products the changes can propagates within the module unless the interfaces between the modules are unchanged. Product family design is extensively used in the industry because of its cost effectiveness, improved productivity and quality. Several engineering change management methodologies have been suggested by the researchers and scholars but they are confined to the single product analysis and very little consideration has been given to product family.

It is evident from the literature that the volume of research accomplished in the field of engineering product/process design change has significantly increased during the last two decades. More academic efforts are needed to develop tools and manage knowledge to facilitate firms to enhance their engineering change processes and produce good quality products.

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