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INFORMATION MODELS USED TO MANAGE ENGINEERING CHANGE: A REVIEW OF THE LITERATURE 2005-2010

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ABSTRACT
Engineering change is a significant part of any product development programme. Changes can arise at many points throughout the product life-cycle, resulting in rework which can ripple through different stages of the design process. Managing change processes is thus a critical aspect of any design project, especially in complex design. Through a literature review, this paper shows the diversity of information models used by different change management methods proposed in the literature. A classification framework for organising these change management approaches is presented. The review shows an increase in the number of cross-domain models proposed to help manage changes.

Keywords: Engineering change, change management, literature review

1 INTRODUCTION
One of the earliest and most often cited formal reviews on engineering change was published by Wright (1997). He reviewed literature between 1980 and 1985 and found very few papers on the topic. Since then, there has been a significant increase in the number of publications on engineering change. This can be seen in one of the latest reviews on change management by Jarratt *et al*., (2010). These two papers provide general reviews on change management, broadly covering every aspect of the topic and also categorising literature. Other review papers focus on a particular aspect related to change management. Rouibah and Caskey (2003) reviewed supply chain issues in change management. Huang (1998) thoroughly reviewed approaches for electronically-managing engineering changes. Browning and Ramasesh (2007) conducted a survey of activity-based network models, where they pointed out lack of consideration of the structure of the detailed design process in methods to manage changes.
In addition to papers studying theory and proposing methods to support change management, others report on case studies conducted to understand the nature of change and identify the problems associated with managing changes. For instance Eckert *et al*., (2005) conducted an interview-based case study and reported findings regarding the predictability of engineering change in complex design . In another case study, Giffin *et al*., (2007) studied past change data and used this to draw conclusions regarding the nature of the change propagation in complex systems. Case studies of change management give new directions and insights into problems faced by designers in industry, and are a source of motivation for researcher as well.
This paper presents the results of a detailed systematic search of the literature on change management published between 2005 and 2010. The paper adds to the existing reviews, for example Wright (1997) or Jarratt *et al*., (2010), in that it classifies the change management approaches based on the forms of information models which are proposed to analyse changes. This highlights the diversity of information models used by change management methods proposed in the last five years.

2 DEFINITIONS
Some of the key terminology used throughout the paper is defined as follows:
- **Function**: We use Pahl and Beitz’ (1995) definition of function as “an abstract formulation of the task in terms of inputs and outputs, independent of any particular solution”.
- **Component**: A product can be divided into a number of components/subsystems. Each component should participate in carrying out at least one function.
- **Design parameter**: An input or output to a design task, which may (for instance) describe some

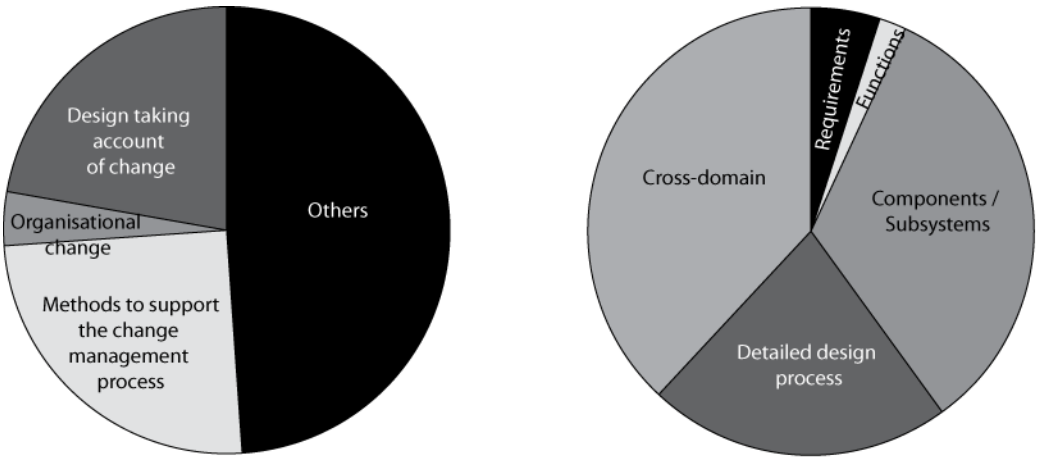
aspect of a component.

- **Design task**: A design task processes some input design parameter(s) to produce some output design parameter(s).

3 METHODOLOGY

The methodology to conduct the literature review focused on selecting journals/conferences to review, determining the time period for the review and identifying criteria for filtering papers:

- **Journals and conference proceedings reviewed**: A number of main journals and conferences related to design and design management were used as the source for literature on ECM. The journals considered were: Research in Engineering Design; Journal of Engineering Design; IEEE Transactions on Engineering Management; Product Innovation Management; Computers in Industry; and Management Science. Conference proceedings considered were: International Conference on Engineering Design (ICED); Design; International DSM Conference; and ASME DETC.
- **Time period**: One purpose of this literature review was to identify the latest emerging trends in the published literature. The literature review thus considered all papers published during the last five years in the journals and conference proceedings mentioned above. For the biannual conferences such as Design and ICED, the last three conference proceedings were considered.
- **Criterion for initial selection of literature**: The word "change" was searched for in all abstracts from the identified sources and time periods. 305 papers were thus identified and short-listed.



(a) Division of published literature in different categories b/w 2005 - 2010

(b) Sub-division of literature in the category "Methods to support the change management process" according to the type of model used (publications that do not report a model-based method are not shown)

Figure 1: Summary of the papers found in the literature survey, covering 2005-2010

The literature selected in the initial phase was classified into the following categories (Figure 1 (a)):

- **Methods to support the change management process:** The literature related to directly supporting any of the stages of the Engineering Change Management Process was included in this category. Papers reporting surveys and case studies to understand various aspects of the change management process were also considered in this category.
- **Design taking account of changes:** This category included the literature discussing the possibility of designing a product so that it can adjust to changes in requirements, legislation and other factors. For instance, papers on flexible design / design for flexibility, innovative design and robust design were included in this category. All these subcategories discuss product design which will have the ability to tackle future changes. Moreover, literature involving changes in the manufacturing process such as concept generation, mass customization and lean manufacturing were also included in this category.
- **Organizational change:** Papers discussing the impact of changes on operations in an organization were included in this category.
- **Others:** All the papers which had been shortlisted but did not fit any of the above-mentioned

criteria were included in this category.

Figure 1 (a) shows the proportion of papers in each category. From the 314 papers initially selected, 25% (78) were in the first category listed above. These 78 papers form the basis of the review.

4 CLASSIFYING APPROACHES TO MANAGE CHANGES

The literature review revealed a variety of ECM methods which use models to support change management. The methods vary not only in terms of their analysis of changes but also in the information that they require to do this analysis.

The following section classifies change management methods based on the information model used to manage changes. This classification was generated from the findings of the literature review. The ECM methods are classified into three main categories and are then further classified based on the details of the model used. The main classification categories are: Single domain methods; Cross domain methods; and Others. Methods falling into these categories are discussed in the following subsections.

4.1 Single domain methods

The literature survey show that 46% of the change management methods proposed between 2005 and 2010 are based on information models from only one domain of product development: either requirements, functions, components or the design process.

4.1.1. Requirement models

Change in requirements is one of the main sources of change initiation during design. Deubzer *et* al., (2006) reports in the findings of his survey that the majority of changes arise from change in requirements. Usually requirements are used with other design information when tracing the effects of change; these methods are discussed in Section 5.2. In this section, methods are discussed that only use requirements information to assist in managing changes, mainly focusing on the use of requirements to trace the effects of a change.

Kilpinen *et al*., (2006) discusses a change impact analysis technique in software using the requirements between system-design and embedded-software (Kilpinen *et al*., 2006). In this method requirements are used to trace changes to related design documentation. Bapat *et al*., (2007) presents a method to store design knowledge so that the requirements are mapped to a computer-interpretable form, which makes it easier to adapt to changes in requirements. An algorithm is developed which identifies the multiple requirement changes and gives the designer options to explore different alternatives. Other researchers have suggested strategies to help deal with change in requirements. For example Peterson *et al*., (2007) suggests strategies to cope with the changes that propagate from changing requirements.

4.1.2. Function models

Approaches which use functional models to manage change are usually used alongside components or subsystems models. These methods are discussed in Section 5. In the review of recent literature between 2005 and 2010, only one method was found that uses only a functional model to consider the impact of changes. This method, proposed by Rizzuti *et al*. (2006), shows how the impact of changes on the product can be assessed using functional nets. In the method, the functional net describing a product is divided into four sub-graphs termed as layers (energy; material; signal; and force layers). The linkages between these layers are used to generate alternate solutions for changes.

4.1.3. Component/subsystem models

Most of the single-domain methods found in the literature are based on component/subsystem models. Figure 1 (b) shows that 22% of the change management methods found in the literature review use component models alone. The methods in this category assist various kinds of analysis, as discussed below.

The Change Prediction Method (CPM) by Clarkson *et al*., (2004) is one of the most cited examples of the approaches using a component model alone. The CPM is based on a model of the linkages between components in a product. For each link it also requires the likelihood and the impact of change propagating to the connected component. These values are used to calculate a risk matrix, which shows the risk of change propagating from any one component to any other, taking direct and indirect paths into account The CPM method has been applied to a number of ECM problems:

- Ariyo prioritises the risk calculated using the CPM so that the most risky components can be looked at thoroughly. A “change risk prioritisation number” is generated for all the components; this is similar to the risk prioritisation number used in Failure Modes and Effects Analysis methods (Ariyo et al., 2007b). Ariyo et al. also use a component-to-component, component-to-system, system-to-component and system-to-system likelihood to estimate the impact of change (Ariyo et al., 2007c).
- Keller et al., (2007b) discuss strategies to use the CPM and Contact and Channel Method (C&CM) together to manage changes (the latter captures both components and functions).
- Koh et al. model the relations between design features and components to help assess change requests (Koh et al., 2009). In this context, a feature is a property of a component.

Design freeze is a common practice in design, in which the design of some components is frozen to avoid change thereafter. Component models have been used to determine the design freeze strategy of components, for example in the method proposed by Eger *et al.* (2005). An algorithm to determine the optimal design freeze order based on the CPM’s combined risk matrix and the redesign cost of each component is presented by Keller *et al.*, (2008).

Component models have also been used to design products from the points of view of flexibility and concept evaluation. De Weck used a “delta DSM” to compare a baseline system with the changed system (deWeck *et al.*, 2007), helping to identify all the modifications that may be needed to implement a particular desired change. Keese *et al.* (2006) analyse product design for flexibility using an enhanced Change Modes and Effect Analysis (CMEA) method, which they adapt by changing the scales of design flexibility and by providing a rubric to calculate CFR. They propose this method can help to assess product flexibility and to determine the cost of changes. A six-step method to assess the impact of engineering changes is presented by (Kohler *et al.*, 2008), which is intended to be used in early stages of product development when describing the product.

Other component models used for analysing changes were proposed by (Zhang *et al.*, 2006) and (Waldele *et al.*, 2007). Zang *et al.* present an algorithm to deal with changes in plastic parts during mould design and Waldele *et al.* use the different properties of components (organized as a network) to understand the total changes required to meet a change in requirements.

4.1.4. Design process models

In terms of ECM, design process models are usually used to see the impact of changes in terms of the (re)design activities and design parameters affected. Figure 1 (b) shows that 16% of the methods identified use a detailed design process model in support of change management. These are discussed below.

Ouertani *et al.*, (2007) discuss a method based on a data dependencies network, which is used to identify alternative strategies for rework in design activities in case of changes in design. Another method by the same author assesses the impact of changes when changes are a result of conflict resolution in a concurrent engineering environment (Ouertani, 2008). The same paper discusses strategies for overlapping activities from a change viewpoint. A simulation-based approach to show how design rework can be effectively prioritised (i.e., planned) using change prediction techniques is presented by Wynn *et al.* (2010); this approach equates process steps with components requiring rework. Flanagan *et al.* (2005) discuss the influence of design activities’ properties on the amount of rework required in case of design changes, and consider how the design activities can be re-ordered for more efficient execution based on resource constraints. A virtual method that combines parametric data with graphical data is presented by (Kocar and Akgunduz, 2010). This method assists users to comprehend change and presents a technique to prioritise change requests by mining historical data.

Creating dynamic workflows is another way to deal with a design environment characterised by change. Joshi *et al.*, (2005) present a method to create dynamic task workflows from knowledge about the (re)design. Similar approaches to handle changes in the process by creating dynamic workflows are presented by (Qiu and Wong, 2007) and (Shiau and Wee, 2008).

Kolberg *et al.*, (2007) suggests that an engineering change management plan should include design methodology that suits a particular industry; and indeed some of the methods that were found are intended for particular industries or contexts. Kilpinen et al., (2007) and de Costa et al., (2007) present change management methods for software companies. Change management procedures for specific cases are also considered by (Amaral and Rozenfeld, 2007); they use distinct models to generate a change management procedure for a specific case.

4.1.5. Summary of single-domain methods

Table 1 summarises the single-domain change management methods reviewed in sub-section 4.1.

Table 1: Summary of change management methods focusing on a single domain

Focus	**Advantages**	**Disadvantages**	**Method of analysis**	**References (e.g.,)**
Requirements	Allows to trace changes from its source	Use other design information	Traceability	(Peterson *et al*., 2007)
Functions	Allows innovation in design	Time consuming to construct functional models	Linkage between functions through sub layers	(Rizzuti *et a*l., 2006)
Components	Risk of change in all components is available	Eliciting info. such as likelihood and impact of change between components	Probabilistic	(Keller *et al*., 2007b) (Ariyo *et al*., 2007b) (Eger *et al*., 2005)
	High level overview of change propagation to all components	Limited analysis in terms of rework effort required	Linkage between components	(Kohler *et al*., 2008) (Ariyo *et al*., 2007c) (deWeck *et al*., 2007)
Process	Detailed analysis	Requires more time to make a detailed design process model	Task properties	(Wynn *et al*., 2010b) (Kocar and Akgunduz, 2010) (Flanagan *et al*., 2005)
	Better resource management due to design activity level information	Relatively complex models	A network of design tasks and parameters	(Ouertani *et al*., 2007) (Joshi *et al*., 2005)

4.2 Cross domain methods

While the majority of ECM methods are based on models of information from a single domain, there has been a recent and significant increase in the use of cross-domain information models to understand or help address engineering problems. Among the change management methods found during the systematic literature review, 27% use some sort of cross-domain model to manage changes (see Figure 1 (b)). After further analysis, these methods were sub-classified into the following four categories:

- Requirements – Functions – Components
- Functions – Components
- Components – Detailed design process
- Across all stages (Requirements – Functions – Components – Design process)

These methods are discussed in the following subsections.

4.2.1. Requirements – Functions – Components models

Most of the papers on change management usually discuss changing requirements as a source of change in products. In this category, we only consider those methods which specifically exploit the relationship between functions and requirements to identify the affected components. There was only one method found during the systematic literature review which captures this relationship and discusses its use to support change management (Boersting *et al*., 2008). This method uses the relationship between requirement and function to identify linkages between components. Specifically, the C&CM method is used to map the requirements and functions of a product to its components, then the CPM method is used to find the risk of propagation using the identified linkages.

4.2.2. Functions – components models

The relationship between the functions and components of the product is often thought to be very important, especially at the conceptual design stage. Understanding this relationship has been said to allow the designers freedom to explore different solutions and thereby to support innovation (Pahl and Beitz, 1995). Most of the cross-domain ECM methods found in the review are intended to create or explore design solutions which can adapt to future changes – such as ‘design for flexibility’ and ‘design for innovation’. Covering the literature related to these topics is out of scope of this review. Rather, this section focuses on the methods that use a model of the function-component relationships in a product to help manage changes.

Ariyo *et al*. (2006b) discuss a method to assess propagation of changes by recording structural, functional and behavioural relationships between components. Functional relationships are recorded by mapping the functions of the product to different components. An MDM approach that maps components to design features is presented by Koh *et al.* (2009). It uses the relationship between component and design features when identifying the design attributes that will require change. Price *et al*. (2006) uses a layered approach to connect functions, components and electrical qualitative grid to help monitor changes in the electrical design process. This provides the basis for a design safety analysis tool.

4.2.3. Components – Design process models

One of the disadvantages of the component-based models was that the focus on a product restricts the level of detail of an impact analysis of change. The methods classified in this category tend to exploit the relationship between components and design parameters to identify the design activities that may require rework as a result of change. Gärtner *et al*. use a product - process DMM to identify the design tasks affected by change (Gärtner *et al*., 2008). The simulation method presented also calculates rework in the activities and consequently estimates the impact of this rework on lead time. Lee *et al.* also uses a design dependency network to calculate the relative change impacts for each component and system (Lee *et al*., 2007). This kind of analysis enables users to concentrate on the components and systems which can suffer more impact due to changes.

4.2.4. Models including all considered domains

Most of the cross domain information models used for managing changes fall under this category.

Xue *et al*. (2005) present a method that traces changes in design descriptions from the conceptual design stage to the detailed design stage. The elements of each stage are considered as design descriptions and each stage is termed as a world. Another method that used different information in the design for managing changes is proposed by Karnik *et al*. (2005). Gumus et al. discuss a product lifecycle approach to assist in change management (Gumus *et al*., 2008). This method uses information from multiple domains to assess the impact of change at different stages. Eger *et al.* presented a framework to assess change impacts in different stages of product development (Eger *et al*., 2007).

Other methods considering the lifecycle of the product are presented by Wang *et al*. (2007), Bergsjo *et al*. (2007) and Ma *et al*. (2008). Wang *et al*. used the relationship between life cycle cost model and part variety in product family to assess the impact of a change, which is determined by quantitatively analysing this relationship. An example of such relationship is that when a part change occurs then some parts become redundant. Bergsjo *et al*., highlights some key limitation of the current Product Lifecycle Management systems and proposed plug-ins for better change management through the lifecycle of the product. Ma *et al*., developed an algorithm that predicts changes in information consistency between stages of a multistage model of product lifecycle.

Eckert *et al*. (2008) discussed the effects of changes in supply chain due to changes in the product. A new methodology to predict, analyse and assess changes in a multistage manufacturing environment, such as aerospace, automotive, electrical appliances, etc, is presented by Du *et al*. (2008).

5 OTHER METHODS AND EMPIRICAL STUDIES

The ECM methods found in the literature which do not use an explicit information model, or where the form of information model could not be clearly delineated have been classified as ‘others’ in Figure 1 (b). This category also includes the surveys and case studies conducted to understand and to highlight various aspects of change management. 27% of all the change management literature found falls under this category.

The techniques suggested to manage and to control changes which did not clearly fit into a prior category were:

- A technology infusion framework to assess the change propagation due to technology infusion (Suh et al., 2008).
- A mathematical model to assess the cost-to-value impact of design change (Tseng et al., 2008).
- Baselining to mange changes in design artefacts, so that when a design evolves it is compared against the baseline (Wie and Flechsig, 2009).
- Use of change classification to assist in managing changes (Waldman and Sangal, 2009).
- A path based method using the dependency information and a pattern based method using the DSM to evaluate different change options (Li and Rajina, 2010).

Change management methods which are aimed at mitigating or controlling the impact of change are presented by Li and Chen (2010), Xue *et al*. (2006) and Vianello *et al*. (2008). Xue *et al*. (2006) presented a method to find the most suitable design from the coupled and decoupled design. Ideally a design configuration should be as independent as possible from its implementation process, so it would the changes would be less likely to propagate. Vianello *et al*. (2008) related changes in the service phase to the product development process, in order to identify the design phase which should be modified to reduce the effect of these changes. Li and Chen discussed a pattern based proactive approach to redesign requests which limits change propagation (Li and Chen, 2010)

Some other change management methods classified as 'others' include a variety of methods. Hani *et al*. presented a model for change management that identifies the information needs for manufacturing process planning engineers (El Hani *et al*., 2006). A method to store design information using XML documents, which is proposed to enable automatic change detection, is also classified under this category (Bae and Kim, 2007). Finally, Khudyakova and Danilovic (2007) used system level co-ordination between multiple projects to see the change propagation across projects.

5.1 Surveys

A number of papers reported on surveys which aimed to understand an aspect of change management. Deubzer *et al*. conducted a survey to explore the main reasons of change initiation in the product (Deubzer *et* al., 2006). Requirements were identified as one of the main sources of change initiation. Sudin and Ahmed carried out a survey of occurrence of changes during the lifecycle of a product as a consequence of change in requirements of the product (Sudin and Ahmed, 2009). A total of 271 change requests were reviewed to understand different factors involved, including: drivers of change, sources of change, time of initiation of change etc.

Ahmed and Kanike conducted a survey to understand the occurrence of changes during different stages of the lifecycle of a product (Ahmed and Kanike, 2007). 1500 documents were reviewed to analyse the different sources of change during different stages of product development. Finally, a survey to assess the impact of product change intensity on a PC manufacturer's success is reported by Hua and Wemmerlov (2006).

5.2 Case studies

Three main publications between 2005 and 2010 were found to describe case studies focusing on change management issues. The first study is reported by Eckert *et al*., who discuss issues impacting on the predictability of engineering changes in helicopter design (Eckert *et al*., 2005). Different factors are identified which may influence the prediction of engineering changes. They identified that prediction of change mainly relies upon the uncertainties associated with a particular situation. The second case study was reported by Giffin *et al*. in 2007 (Giffin *et al*., 2007). In this case study over 42,000 change requests were analysed to understand the behaviour of engineering change propagation in complex systems. The main conclusions of this case study were: change propagation is very common in large technical systems; the occurrence of changes is not uniform through out the product development; and related change requests are generated in indirectly-connected areas.

In the third case study, Kilpinen *et al*., (2009) observed different impact analysis (IA) techniques used in an aerospace company. Based on this case study, they develop a classification framework to classify various IA techniques. The framework comprises of the following main categories: Traceability impact analysis; Dependency impact analysis; and Experimental impact analysis.

6 SUMMARY AND CONCLUSIONS

Engineering change initiated in requirements, functions, subsystems, or as a result of iterations in design requires a change process. One of the main difficulties with managing this process lies in the innate nature of change to propagate both within and across domains. For example, if a change is initiated in requirements it will affect functions, components and parameters of the design, and require rework in the design process. Most of the widely-cited change management techniques in the academic literature, such as CPM and Redesign-IT, consider changes at the component or parameter level alone. The literature review presented in this paper highlights that a lot of recent publications have proposed change management methods based on models which use information from other domains.

In terms of numbers of publications, most of the methods based on single-domain information models are component/sub-system-based. In second place are the methods which use only models of the design process to identify rework following change. Only 4% of the papers we found use requirement specifications alone in their approach to address a change-related problem. Likewise, only 4% of the methods use functional models alone. Many more techniques do use functional information to help manage changes, but these also consider models of the component or subsystem of the product and are thus classified as cross domain models.

To summarise:

- In the last five years, a significant amount of literature has been published regarding different aspects of change management. 78 papers were found proposing methods to support change management, based on models capturing the connections between requirements, functions, components, and/or process-related information.
- Models of information from different domains are widely used in the literature proposing approaches to manage changes.
- Many papers which aim to help manage changes use cross-domain information models. 8 papers were found proposing cross-domain approaches to support change management in 2005, and our survey found a steady increase in publications per year since then. In total, 38% of the papers reviewed fell into this category.
- Relatively few papers reported empirical work (case studies or surveys) aiming to understand change management practice or issues.

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