METHODS FOR ENGINEERING CHANGE PROPAGATION ANALYSIS

Rutka[1], Guenov[2], Lemmens[2], Schmidt-Schäffer[3], Coleman[1], Rivière[4]
[1]Airbus, [2]Cranfield University, [3]EADS Germany, [4]EADS CRC France

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Abstract

The aim of the methods described in this paper are to simulate and analyse the propagation of changes in an engineering product, process and/or organisation, so that time, cost, and resources can be allocated according to the impact of the change. The paper presents advanced concepts for capturing dependencies between such viewpoints of the overall engineering system. In the proposed approach, simple Boolean dependencies and dependency strengths can be described along with types and levels of change. The objective is to define dependencies more completely by taking into account that the number and the strength of these may vary throughout the product lifecycle. Case studies from the aerospace industry are being used to test the advantages and limitations of the proposed engineering change propagation analysis methods.

1 Introduction

Changes to the design of a product occur frequently during the various phases of the product development lifecycle, from concept, through definition and development, to manufacture, and then into service. Changes are required to fix problems or to improve or update products. It is often the case that new products are variants or derivatives of existing ones. Hence, changes can have different origins or nature, and often not all the consequences of a given change are expected or wanted. The effectiveness and efficiency with which a company can predict or control these changes could have a significant impact on its competitiveness.

In a complex product, where the constituent parts and systems are closely dependent, changes to one item of a system are highly likely to result in a change to another item, which in turn can propagate further. It is widely acknowledged [14] that change propagation analysis (CPA) is necessary for predicting and simulating the impact of change, in order to improve the capacity to manage time, cost, resources and quality. Current practices for analysing the propagation of engineering changes (ECs) often use configuration management procedures and rely heavily on human communication, the knowledge and experience of individuals in a specific system area, as well as common sense. Due to the globalisation and fragmentation of the aerospace and other industrial sectors there appears to be a need for a more integrated and shared CPA approach within organisations and across their supply chains.

Therefore, the objective of this research is to develop an approach to support decision-making in EC processes and the discrimination between concept alternatives [24]. Also, a shared view between all actors could enable a better understanding of the collaborative and concurrent environment. Furthermore, the approach should enhance the anticipation and identification of key design levers and ultimately improve the design robustness.

In this context, the methods discussed in this paper attempt to capture knowledge about dependencies within systems and related information more completely and exploit this knowledge to identify the possible impact of an

EC. In the proposed model, dependency properties are described, taking into account that different types and levels of change occur during the product lifecycle, along with impact on decision criteria.

The remainder of this paper is organised as follows. Section 2 reviews the state-of-the-art in terms of methods for engineering CPA. Section 3 explains the proposed engineering CPA method. Section 4 introduces the case studies being used in the VIVACE project to identify types of engineering change and dependency relationships that typically occur within the aircraft design process. Finally, Section 5 provides conclusions and outlines future directions for the research.

2 State-of-the-Art

2.1 Overview

Early research on engineering changes focussed on improvements of project management techniques and optimisation of design processes [12]. Current research deals more with building synthetic models of product information. Major publications in this field have been produced by EDC[1] [7], TUM[2] [10] and GIT[3] [4]. Also work by MIT[4] on product models [20] and on Axiomatic Design [26] has contributed to the understanding of the impact of ECs.

Standards relevant to the aerospace industry are ISO 10007 [13], RG AERO 00023 [21], MIL-HDBK-61B [17], ANSI / EIA 649 [1]. These standards provide some recommendations and guidelines for the implementation of configuration management best practices. They specify some generic change processes and highlight the need to identify and control the impact of change requests although they do not provide any change impact analysis models or methods.

2.2 Dependency Modelling Methods

In order to simulate change propagation and its impact, the relationships between different elements of the overall engineering system and associated information have to be described. Two distinct approaches are the qualitative and the quantitative description of the relationships. Qualitative relationships indicate approximately how much interaction there can be between two items. On the other hand, quantitative relationships use physical parametric formulae to describe the dependencies that can automatically identify how much the affected parameters will vary [27]. Although the qualitative approach can be less precise, results can be obtained much faster than the quantitative approach. Hence, it appears to be more easily applied to complex systems. These relationships or dependencies can be visualised in different ways. Early dependency models for activity scheduling used digraphs to depict dependencies [18]. More recent prototypes use Design Structure Matrices (DSMs) [25] and Domain Mapping Matrices (DMMs) [6] to model Boolean dependencies. In computer systems, dependencies are often stored in databases and are visualised as a set of tables.

An alternative approach is the use of agents [11]. An agent can be seen as a software tool that uses a common communication protocol and common data representation to be able to exchange information. This way, an engineering change can be communicated across a network that connects everyone involved in the development process.

2.3 CPA Methods

A general framework for EC impact analysis based on an integrated design information model has been proposed by Ma et al [16], as shown in figure 1. This model combines product data, process data and (organisational) resource data but does not propose any dependency models in detail.

[1] Engineering Design Centre, Cambridge University (UK)
[2] Technische Universität München (Germany)
[3] Georgia Institute of Technology (USA)
[4] Massachusetts Institute of Technology (USA)

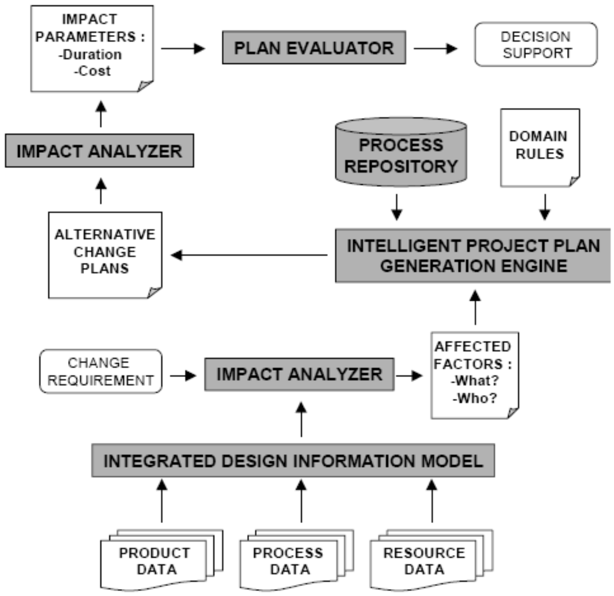

Fig. 1. EC impact analyses framework (Ma 2003)

Simple EC propagation simulation methods are based on qualitative models using Boolean dependencies. More advanced models extend the dependency with some additional information. Often, dependency strengths are specified in a model [5]. A limitation of associating the level of strength to the dependencies is that it is independent of the EC characteristics. Hence, the dependency strength can only have limited (or doesn't) influence on the outcome of the overall propagation simulation.

Different classes or types of dependencies have also been used to characterise the propagation in more detail. A model called Collaborative Management of Engineering Changes (CM-EC) [22], uses six types of dependencies between system components. Jarratt [15] extended the Change Prediction Method (see below) with different links (dependencies) based on mechanical, electrical and thermal functions. A limitation of these approaches is that the types of impact or change of the affected items are independent of the types of change of the initiating items and hence it is not taken forward during the propagation.

One of the most advanced models to predict change propagation is the Change Prediction Method (CPM) [3]. This method is based on two DSMs and models the dependencies between system components in terms of likelihood and impact ranging on a scale of 0 to 1. Propagation paths are identified by an algorithm that calculates the risks of propagations based on the likelihood of changes between each item and the impact of such a change. A limitation of this approach is that it does not characterise the (component) changes itself, but predicts the risk associated with the amount of rework or cost based on the probability and impact on the cost. Another disadvantage of this method is that for larger models, the computational effort increases rapidly.

Flanagan et al [9] propose a method for predicting change propagation that is based on dependencies between parameters that design tasks use as inputs and outputs. Change Process Planning [8] combines CPM with Signposting [2] to help indicate design activities that result directly from change. Cohen [4] describes the C-FAR method where each part in the product structure is associated with a set of attributes. Dependencies between the attributes of the different parts are used to analyse the impact of an EC. Other methods for impact analysis of ECs use dependencies between design parameters. These dependencies can be directional [19], or based on maturity levels and the status of the parameters [23].

3 Proposed CPA Method

3.1 Method Outline

The proposed change impact and propagation analysis method is based on a dependency model considering 3 main aspects.

First, the model can contain information that represents several viewpoints or domains of the engineering system, for example requirements, product architecture, design processes or activities. The information items associated with each viewpoint or domain are the key entities within the model.

Second, the model can contain additional dependency information that describes the links or relationships between two items. These can be items from the same domain or items from different domains. For a change of a given item, a propagation simulation can then be used to trace the possibly affected items. To further support the decision-making process, the impact on specific decision criteria (e.g. cost, delays, etc.) can also be identified.

Third, such models will evolve as the overall design representation matures and the corresponding engineering organisation changes throughout the product lifecycle. These models can also be used as a baseline for new versions of the product.

3.2 Items

Each item belongs to a domain and is associated with a number of descriptive attributes. A key attribute is the milestone in the product lifecycle at which the item will be frozen, i.e. that it should not be changed from this milestone onwards.

During a CPA, an item can also be associated with different types of change (ToC's). The ToC specifies the property of the item that is changed, e.g. material or geometry. Each ToC is then given a level of change (LoC) which reflects the amount of rework or change required from the current configuration baseline.

3.3 Dependencies

To perform an accurate CPA, a precise qualitative description of the change of items and the dependencies is required.

As illustrated in figure 2, a dependency is defined between an initiating item (I-item) and a target item (T-item). In our method, the dependency can be specified in more detail by defining the ToC for the I-item and the corresponding ToC for the T-item. Also, a LoC can be defined for each ToC. Consequently, the ToC and LoC of an affected item will depend on the ToC and LoC of the initiating item. Multiple dependencies can be defined between 2 items for modelling different impacts for various initiating LoC's and ToC's.

Furthermore, in our method, dependencies are also accepted between different ToC's of the same item. This can be used to take into account the interdependency between the ToC's. Additional attributes of a dependency can include the milestones or the range of the product lifecycle at which the dependency is valid, a likelihood value, description, date, the source and owner.

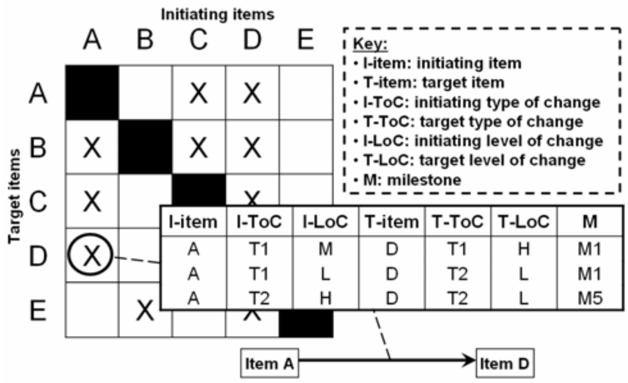

Fig. 2. Example of basic dependency definition

3.4 Change propagation simulation

A change propagation simulation is based on a specified initiating item. The ToC and LoC of the change of this item can also be specified together with the milestone. If no ToC, LoC or milestone is specified, all ToC's, LoC's and milestones are considered. Furthermore, the domains of interest are selected.

For the first propagation step, the CPA will search for all the dependencies with an initiating item that matches the specified item and that affects items in the specified domains. If also a ToC and a LoC have been specified, dependencies with the matching I-ToC and I-LoC will be queried. The found dependencies will identify affected items and their affected ToC and LoC. The affected items with identified ToC and LoC will become the initiating items for the next propagation step. The propagation continues accordingly.

The propagation will not continue when, obviously, no further dependencies exist. Also the propagation is not continued for affected items that are frozen for the considered milestone. Nevertheless, propagation loops can occur, where newly identified items affect previously identified items. Therefore, the propagation can also be interrupted when a previously identified item is encountered, in order to prevent an endless propagation. In the case ToC's and LoC's are used, the propagation is only interrupted for an item with same affected ToC and for a LoC that is lower or equal to the LoC that has been identified before for this item. This is based on the assumption that in this case no new items or ToC's will be identified. In case the LoC is higher than previously identified, then it can be possible that new impacts with a higher LoC will be identified. Finally, the propagation can also be terminated after a specified number of propagation steps.

A tree representation of a simple propagation simulation is shown in figure 3. Item A is the initiating item and no ToC's are used. LoC's are considered but not shown. The 3 cases for terminating the propagation are indicated.

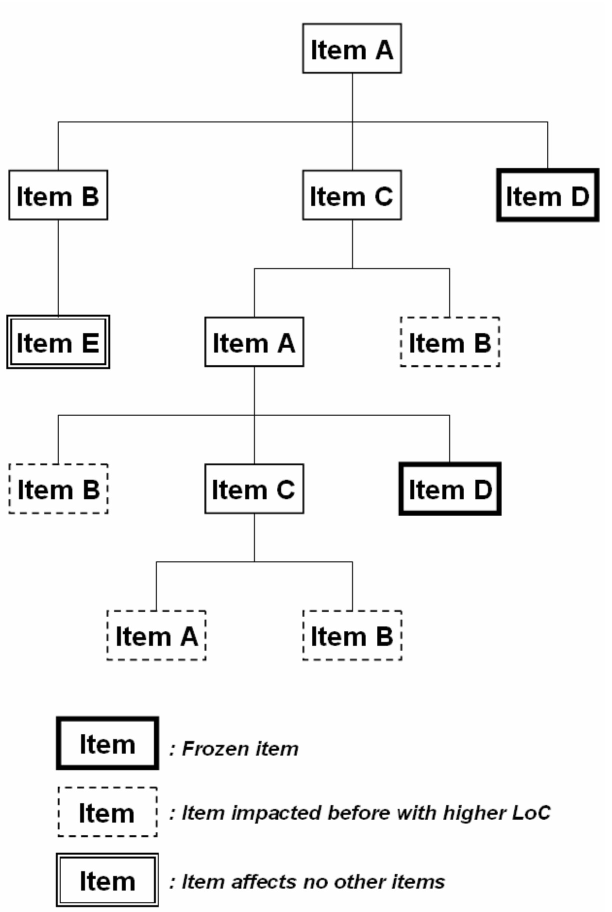

Fig. 3. Example of propagation tree

3.5 Decision criteria impact analyses

The final LoC for every item for each ToC at the end of the propagation is the maximum LoC that is encountered when propagation loops are interrupted as described above. To be able to use the outcome in decision making process, the risk related to decision criteria (cost, time, etc.) has to be identified. The level of risk depends on the (level of) impact and the likelihood (probability) associated with the criteria.

In our approach, the level of impact on the criteria and the likelihood are based on the maximum LoC's and ToC's derived from the propagation analysis. This is based on the assumption that the risk for each criterion is directly related to the maximum LoC and ToC for each item.

Therefore, the risk can be calculated directly as a post-processing step after a propagation analysis. This means, after the propagation analysis, the final LoC for each ToC of every item is used to determine the level of impact and likelihood for each criterion. The latter values are used to calculate the risk for each criterion. A global risk is then derived for each criterion based on the combined risk values for every item.

The computational power required for this approach is minimal as the level of impact and likelihood are obtained in one step.

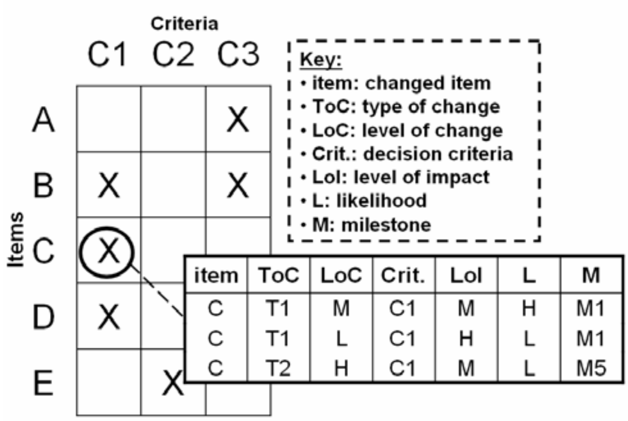

Fig. 4. Example of criteria impact dependencies

4 Case Studies

The CPA method presented in the previous section has already been implemented in a prototype software system. The software architecture used is not discussed in this paper. The method and software are currently being evaluated on a number of different case studies.

The case studies are building dependency models using information from current Airbus design programmes, and each is related to the application of change impact analysis to examples of major components of the aircraft e.g. nose, cockpit, wing, landing gear, pylons, nacelles.

Use Case	UC1 Nose	UC2 WDA	UC3 WCA	UC4 Pylon
Domains	6	7	5	7
Items	91	346	68	114
Dependency Links	1108	2358	70	800
Dependency Relationships	2400	2358	77	1400
ToC	25	12	18	20
LoC	4	4	4	4

Table 1. Current size of models for the Case Studies

The current size of the models being constructed and evaluated for four of the case studies is indicated in Table 1, in terms of the number of domains considered in the model, together with the total number of items and the dependency links and relationships described.

The models shown in Table 1 cover a range of different use cases: nose / cockpit structure and systems installation architecture behaviour (UC1); wing and landing gear design and integrated development programme analysis (UC2); wing concepts analysis considering 3 different aircraft configurations (UC3); and engine pylon design architecture behaviour (UC4).

Several of the domains (or viewpoints) considered are common across the case studies. For example, all the case studies here consider the product requirements as an important information domain, both in terms of understanding the dependencies between requirements as well as the impact of changes in requirements on items from other information domains such as physical or functional architecture. In addition, UC2 also considers the dependencies between the tasks (activities) being carried out as part of the wing design programme, together with the disciplines or different teams within the organisation that are required to carry out the tasks.

As described earlier (see figure 2), a link between 2 items may be defined in terms of multiple dependency relationships. Thus, from Table 1, it can be seen that for UC1 and UC4, there are many dependency links with multiple relationships defined. Whereas, currently for UC2, all the links have only a single dependency relationship defined.

The case studies also consider the impact of change at different phases of the aircraft development lifecycle. Thus, the major milestones of the Airbus “develop new aircraft” process can be associated with both the items and the dependency relationships between them.

Different ToC’s are emerging as the case study models gain maturity, but thus far, a simple scale of low, medium or high has been adequate for describing the LoC’s.

Finally, each case study has run different scenarios to test the CPA method described in this paper, within and between different combinations of the domains considered in each model.

5 Conclusions

This paper has presented various aspects of a dependency model and method for change propagation analysis (CPA) in an aircraft design context. Different viewpoints of an overall engineering system can be accommodated and decomposed as sets of relevant information items. The dependency relationships that exist between items can be described qualitatively. Various properties can be associated with the dependencies such as the ‘strength’ of the relationship and validity during the aircraft development lifecycle. The information is used to simulate and analyse the propagation of a change in any of the described items. The CPA method can be applied within a single domain (viewpoint) or across multiple domains and can also identify the impact on specific decision criteria.

The main limitation of the proposed CPA method is that the quality of the analysis results depends heavily on the accuracy and completeness of the information stored in the model. Since all the relevant information is usually distributed over many domain experts and knowledge bases, capturing all this information can be very time-consuming. Therefore, it is important to maintain the right balance between the time spent to create a model and the time that can be saved by using the model.

Future work will continue to improve the prototype software system that has already been implemented. Particular areas include extending the current risk analysis, improving the project planning analysis, and investigating how to indicate the robustness of a design. The software and the method will thus continue to be evaluated and validated, extending the case study applications towards exploitation in an operational environment.

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