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ENGINEERING CHANGE PROCESS: STATE OF THE ART, A CASE STUDY AND PROPOSITION OF AN IMPACT ANALYSIS METHOD

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Abstract:
The main challenge for product designers, especially of complex products, is to predict as finely as possible the consequence of the product change for its structure as well as its propagation overall the Technical Information System (TIS). Starting from the work already undertaken in this domain, we underline the lack of methods and tools of impact analysis. Our contribution is therefore to bring a method with the aim to facilitate the impact analysis in a multi TIS context. This method, based on a product model supported by a constraints resolution tool, will allow resolving the various constraints levered in an impact analysis problem.

Key words: Engineering change management, impact analysis, PLM, product modelling, integration, CSP.

1 Introduction

Each product implies a great number of design choices. The ideal, to maintain competitive advantages or to correspond to the technological innovations with the competitors, is to get the right design the first time. However, changes due to immature decisions, changes in customer requirements or evolutions of manufacturing processes are unavoidable. Thus, Engineering Change Management (ECM), taking a great part in the development of product, is a vital and a necessary process in industrial companies. According to Maull and al., industries that identified the process of ECM as a principal problem were promoted in the development of their process [1]. This is all the more critical as product engineering proceeds in a simultaneous and a collaborative way. Indeed, in a mechanical design context, Numerical Command Control activity is done by the planning department in a concurrent way compared to the design department. A mechanical part coming from the design department continues evolving whereas the planning department has already achieved the associated machining program and sometimes launched machining process.

This research studies ECM process and focuses on techniques likely to manage the impacts of engineering changes given on a part or on a machining process. The optics is to propose the first elements of a methodology to analyze the impacts of a mechanical part change on the machining process following:

- a change given to a part by the design department : design change
- an evolution of machining means given by the planning department : process change
The first section of the paper presents the ECM process and various related research works (Section 2). Then, a special interest is given to impact analysis activity. A study is undertaken to understand the techniques suggested in the literature to support impact analysis (section 3). Starting from this state of the art and towards the problems faced by our industrial partner, an approach of impact analysis is proposed (section 4).

2 Engineering Change Management process: definition and related works

The ECM process can be defined as being the process to introduce modifications on a product in a projected and systematic way [2]. It aims at satisfying design constraints and objectives, facilitating the task of manufacture, eliminating a design conflict, meeting customer requirements or answering the legislative evolution as in the aircraft industry.

Several strategies were defined to control this process [3] [4], leading to several decompositions of this process. However, we can distinguish three main phases in the ECM process:

- Engineering Change Request (ECR): requests for change are collected with the necessary information to process the treatment.
- EC treatment: a feasibility study is undertaken in order to evaluate the economic and technique feasibility of the requested change. The analysis of the EC impacts allows detecting the consequence on the product and the organization. Then, a decision is taken about the continuation of the process (abort or implementation of the change).
- Solution embodiment: the solution is physically implemented, documents are updated and concerned actors are informed.

Regarding this process, several research works were undertaken during the ten last years. These works can be classified into three categories such as represented in Figure1:

![Diagram](image)

**Figure 1. The structure of existing research in ECM**

- **Exploratory works** were interested to understand the ECM process and to extract the problems related to this process.
- Works aiming at proposing organisational solutions tried to rationalize the ECM process by proposing strategies to control it [4] [11], defining elements to improve its performance [3] [12] [13] and proposing new organisations of the process to better coordinate the activities of EC treatment and to reduce delays [14] [15] [16].
- Works focalising to bring technical solutions concern the change traceability and their impacts analysis. Concerning traceability we quote the work of Cohen [17] which
proposes a product model in EXPRESS format. As for impact analysis, several approaches and techniques were proposed, by components interaction modeling, impact probabilities assessment [2] [18] [19], etc.

In this context of ECM rationalisation, a research work was undertaken by the CRAN laboratory within a French national project (IPPOP*) to propose a workflow model supporting the management of conflicts appearing during cooperative design due to a product definition modification [22]. Conflicts resolution is done by driving the decision process undertaken to modify product data further to a conflict. This process is based on a succession of popularisation and mediation phases (Cf. Figure 2):

Popularization: the actor facing a conflict explains the current problem with the choices currently made on the product. He then proves or argues his motivation to modify the current solution by clarifying the negative consequences of the current choices on the product (in terms of product performance, cost, technical feasibility, coherence with contractual conditions, etc.).

Mediation: this action aims at advocating a solution to resolve the problem encountered and in this way to avoid the unfortunate consequences that could be generated by the former solution. It comes from the actor who has just popularized the problem in order to propose the solution, or from another actor concerned by the conflict who would approve the solution proposed by another actor.

Figure 2. UML activity diagram of the conflict resolution process

During popularization phase, actors need a method to assess quickly the impacts of any technical choice made by one actor and then react in the best delays. The aim of this research is to give a method for impact analysis to support popularization phase. In the following, a state of the art related to techniques likely to manage impacts is given (Section 3). Then, the proposed method is presented (Section 4).

3 Research works dealing with impact analysis activity

Impact analysis can be defined as an activity for which a required EC is transformed into a set of changes induced on the product or its manufacturing process. This analysis stage allows evaluating the technical and financial feasibility of a requested change. During last years,

* Integration of Product-Process-Organisation for engineering Performance improvement
many research works have focalised on impact analysis techniques. These works can be classified according to two approaches: by components interaction modelling and constraint propagation and by impact probabilities assessment.

3.1 Impact analysis by components interaction modelling

A parameter-based approach was proposed by Rouibah and al. in [2] using elementary engineering decisions. In this research, the ECM is seen as an engineering decisions-making process. These decisions change or determine engineering variables and the most elementary of these engineering variables are referred as parameters. Parameters can refer to dimensions, as well as forces and movements. Parameters often share complex relationships, which may be represented with mathematical equations, diagrams or tables. The capture of parameter relations during concurrent design results in a parameter network. Then, once a change need is declared, this change is expressed in terms of one or many parameter’s values changes (a change list). As soon as the actors, concerned by the elaboration and the evolution of the parameter to modify, have agreed on the change list and have specified a new draft value, the parameter status will be “in change”. The impact of this modification is then evaluated by propagating the modification through the parameter network. This method only makes participants aware of the existing relation and possible change propagation between the changed and neighboring parameters in the network. The actors concerned by the modification must jointly clarify whether these parameters are actually affected by the change. A new list of changes is then created, containing only the parameters impacted by the change. Then, a workflow to release parameter approves and distributes the parameters to change and their values to the concerned actors. Figure 3 describes this workflow.

Figure 3. A workflow to release parameters [2]

Ollinger and al. in [18] reconcile the problem from another point of view by proposing an approach by constraints resolution through the REDESIGNIT tool. This tool allows evaluation of proposals for redesign plans. These proposals describe which quantity should be changed as well as the nature of these changes (dimensions, tolerances, matter…). The approach uses a direct dependency graph that describes the various relations between quantities. This graph is built basing on the following concepts:

- Quantity: referring to both physical properties of the device components and descriptions of the device’s operation.
- Causal influences between quantities describing how a change to one quantity affects the other quantities. There are four types of causal influences: M+, M-, LIMITS (AS_UPPER_LIMITS, AS_LOWER_LIMITS).
- Constraints on quantities: a constraint is an expression of a design requirement placed upon a particular quantity (FIXED, MAXIMIZE, MINIMIZE, RANGE).

A causal path is thus built. If a change is applied to the quantity at the start of the path, every quantity downstream in the path will be changed as well. Change propagation will take the form of a propagation tree (cf. Figure 4).

![Propagation tree for quantity “piston stroke”](image)

Given a causal pair, the program takes the direction of change in the cause quantity and the type of causal influence involved finding the change in the affected quantity. The program also allows to detect the undesirable side effect of the modification and to calculate the cost and the benefit of such modification. However, the generated redesign plans are abstract; they do not specify numerical values for the quantities.

### 3.2 Impact analysis by probabilities assessment

Even it is sometimes difficult to quantify a change impact on the whole product components, it is possible to predict the risk to change them. Clarkson and al. [19], through the development of a mathematical model, propose a method to predict the risk of change propagation in terms of likelihood and impact of change. This method uses:

- A design structure matrix to model direct dependencies between all the product components.
- A likelihood matrix expressing the probability of modifying the component \( b \) if the component \( a \) is modified \( (l_{b,a}) \).
- An impact matrix expressing the impact of an EC of \( a \) on \( b \) \( (i_{b,a}) \).
- A risk matrix expressing the risk to impact \( b \) if we modify \( a \) \( (r_{b,a}) \), with \( r_{b,a} = i_{b,a} \times l_{b,a} \).

A modification is also propagated in a transverse way between indirectly dependent components. The model uses the same design matrix to express the indirect dependencies by transitivity. The influence of the EC is then the sum of direct and indirect effects.
In a recent research work, Jarrat and al. [20] extended the original technique proposed by Clarkson, by involving counting along propagation paths, through the implementation of Monte Carlo techniques to simulate change propagation, hence greatly increasing the flexibility of the method.

We finally quote HO and al. [21] who developed an analytical procedure to compute progressive probabilities of ECs. The probability of changing a part at one level is affected by the changes in its parent levels. Then, a sensitivity analysis is performed to see how the shape of product structure affects resultant progressive ECs for the lower-level parts in the product structure.

3.3 Resume

To conclude this state of the art, the impact analysis process refers in all studied works to a resolution of a set of constraints. The various tools and methods then proposed approach the problem from the existing links and the relations between the different components of a product. By identifying these relations and based on the constraints imposed by a component on another, the problem is resolved by change propagation. However, in the whole studied works the change propagation is manual, which is difficult to manage for complex products, such as planes. We then underline a lack for a structured and an automatic method of change propagation able to analyze and to propagate quickly the impacts through several TIS. In section 3, we will develop the problematic faced by our industrial partner and then give our proposition to assist impact analysis process.

4 Towards a systematic method for impact analysis

4.1 ECM problems faced by the industrial partner

In a manufacturer of electric motors, an engine is composed of a set of components developed and manufactured inside the organization, but also in cooperation with external partners. Adding to these development partners, various sub-contractors take part to achieve some activities of industrialization and manufacture. The ECM process is then leaded in an extended enterprise context. From the survey we have conducted in our industrial partner to analyse the ECM process implemented in the organization, we deduce that the treatment of an EC order mainly depends on the type of change, its origin and its urgency. Then, a variety of ECM processes exist in the enterprise. We present here a generic process representing the common part of the observed processes. (cf. Figure 5)
Any modification of an article in the CAD system involves a modification index to distinguish the successive modifications. An article is managed by its code and its modification index in the various TIS of the enterprise. The propagation of the modification index in the product structure is done in the PDM system (Product Data Management), already specifying the various existing relations between articles. However, when change propagates, subcontractor uses the old version of the article (with an erroneous index). Indeed, the modification and the evolution of the article index are not taken into account in the CAMM (Computer-Aided Management and Manufacturing), the only Information System (IS) shared with the sub-contractors.

4.2 Impact analysis approach

Our proposal is based on the assistances that can be given to the configuration managers to facilitate the evaluation of EC impacts, by resolving the problem of product data coherence between the various TIS. The objective is to develop a methodology which proposes the possible configuration of the product and/or its manufacturing process following a modification given to a product element or its manufacturing process. Such a methodology is based on two phases:

- modelling the interactions (impacts) product-product and product-manufacturing process,
- using a programming constraints solver which propagates the obtained constraints (interactions).

4.2.1 Phase 1: impacts modelling

To enhance impact analysis, two modelling mechanisms are used:

- To specify dependences between concepts (which are implemented in the same IS or in several ISs), association classes are attached to the links between concepts (cf. Figure 6). Three kinds of dependences are distinguished: class/class (a class modification lead to a modification of another class), class/attribute (a class modification implies a modification of an attribute inside this class or in another class) and attribute/attribute (an attribute modification implies modification of another attribute). In these three cases, the modification of a concept can be on its existence or just on its instance.

![Diagram of concepts dependencies](attachment:image6.png)

Figure 6. Specification of concepts dependencies

- To integrate the various IS models, a “bridge” concept is introduced between each IS model thanks to links of correspondence between concepts belonging to several IS. These links can be of association, composition / aggregation or generalization / specification kind (cf. Figure 7).
This approach was tested within the industrial partner. First each of the existing IS is formalized by adding dependency concepts to allow capitalization of constraints between product concepts. Then, ISs are integrated thanks to correspondence links between the various product or process concepts established in each IS, and several dependency concepts are attached to model the interactions between them. Thus a distributed product model is obtained (cf. Figure 8). Finally, various scripts were developed to implement the various concept thus introduced.

Figure 7. Specification of IS integration

Figure 8. An overview of the distributed product model to support impact analysis
The model obtained above allows any actor identifying:

- the possible changes of a product or process concept (classes or attributes).
- the possible effects on the other concepts (in terms of changing of the existence or the instance of a class or an attribute).

### 4.2.2 Phase 2: impacts propagation

To facilitate the impact analysis, we propose to connect the TIS integrated model, obtained in phase 1 (cf. Figure 8), to a constraint satisfaction programming solver (CSP) which captures from the TIS, the various constraints (dependencies) between product and/or process concepts and provides a list of impacts for each EC introduced on the product or on its manufacturing process. To do that, a correspondence between a constraint satisfaction problem mathematical model and the TIS integrated model is done. In figure 9 the various established correspondences are given.

Once the product characteristics \( x_i \) (variables) to modify are initialised and the constraints \( c_i \) (dependencies) are fixed, the programming constraints solver provides the solution \( R \) by making intersection of the various solution domains \( r_i \) corresponding to the variables values satisfying each of the constraints \( c_i \).

We give here an example to better explain these correspondences. We consider the product characteristics (dimension, durability, tolerance…) and the machining characteristics (tools, schedule…) as variables \((x_1..x_n)\). Given two constraints \((c_1, c_2)\) whereas:

- \( c_1 \): if dimension > XX, then hole machining is impossible.
- \( c_2 \): product durability must be between \( a \) and \( b \).

The solution domain \( r_1 \) is then the dimensions satisfying the hole machining and \( r_2 \) is the dimensions leading to a product durability between \([a,b]\). Once all solution domains are defined, the final solution corresponds to domains intersection.

The ECM analyser has then the various impacts but also the new possible configurations of the product and/or its manufacturing process.

In figure 10, we give a global view of the proposed methodology to support impact analysis process. From the design actor’s expertise, we capitalize the various change impacts by introducing the product-process dependencies in the different TIS. Then, given a change
occurring on a product element and the various dependencies inside the product (with the manufacturing process), the proposed methodology proposes a list of the various change impacts. It proposes also, thanks to a constraint satisfaction problem solver, the various new possible configurations.

![Figure 10. Overview of the proposed impact analysis methodology](image)

5 **Conclusions and Perspectives**

Evaluating the impacts of engineering changes during design process is a highly critical problem in industry and it is usually managed by the actors themselves, based on their expertise. A manual resolution of the various impacts is only possible if the product is very simple (composed of a few number of parts). In case of complex products, such as cars or aircrafts, automatic resolution is necessary to resolve the whole induced constraints. Then the proposed approach addresses specifically complex products. However, since actual CSP solvers are not efficient (in terms of calculation delays) when the number of constraints is very high, it is necessary to apply the proposed approach to sub-units of the product (in order to have a less number of constraints).

ECM process is usually a highly human process and the proposed automated approach to analyze impacts does not substitute human decision making processes. It assists engineers during design review meetings by quickly evaluating the impacts of each change given to the product and by treating the whole possible impacts (engineers may forget some impacts). Moreover, it allows capitalizing the various changes occurring on products and their impacts, so as to constitute a corporate memory that can be reused in future ECM projects. It even allows keeping trace of the various discussions held by engineers during decision making processes (if a workflow engine is associated to it).

However, the proposed approach is based on a manual capture of the various dependences. It requires a big effort of impacts capitalization and capture. This capitalization can be enhanced by building a domain ontology for technical impacts which matches technical changes with their possible impacts, according to various design contexts. Moreover, in order to avoid manual capitalization and capture of dependencies, it will be interesting to propose a system which would deduce automatically the dependences by capitalizing the various decisions taken by the design actors in past experiments of impact analysis. The use of Case Based Reasoning techniques may enable such deductions.
6 References


