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ON THE USE OF FUNCTIONS, BEHAVIOUR AND STRUCTURAL RELATIONS AS CUES FOR ENGINEERING CHANGE PREDICTION

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1. Introduction

Companies often have to carry out modifications to the on-going design of products to satisfy customer requirements or to correct errors to achieve desired goals. The official process for carrying out engineering changes may vary between companies. However, the basic logic of critical phases during a change process is similar [Jarratt 2004]. Once the need for a change has been identified, depending on factors such as the degree of urgency and the company policies, proposed solutions to change problems are evaluated before the change is implemented. Not all components or solution principles can be modified to the same extent to satisfy new sets of requirements without affecting other components within the product. Unforeseen side effects of changes can affect other parts of the product leading to delays in schedules and stretching available resources. When there is a choice between alternative ways for meeting new requirements, designers need to be able to assess the benefits of changes versus the potential costs or drawbacks. Thus accurate predication of the consequences of a change is vital.

Tools reported in design literature use relations between properties of products as cues for identifying paths through which change may propagate between parts of a product. This can be the structural, functional or behavioural relation between entities, which make up the product. Using a tool called Change Prediction Method (CPM) as an example we show that the accuracy of prediction estimates depends on the type of query. Thus highly plausible propagation paths may be ignored if all three types of relations are not considered for each change instance.

2. Approaches to change prediction

A short review of various tools used to support change prediction is reported in [Jarratt 2004]. These tools have two main objectives in the face of change. (1) To provide a measure of the implications of carrying out a change alternative and (2) to enable pointers to parts of a product which may be affected when a change is made to a component. Some tools satisfy only one of these objectives while others achieve both. However, all the prediction tools only support analysis of changes to one component at a time – none of the tools enables an assessment of the collective effect of several changes. Further, there are currently no industrial tools to assist managers with change prediction. Modern CAD systems, such as Catia, can predict geometric clashes between components but they cannot predict the knock-on effect of changes. There are only a few academic tools for predicting change, all of which have shown only limited success in creating plausible estimates for the impact of proposed changes.

An important objective in change prediction is to *assess* the consequences of making a change. Most of the tools used to predict change impact carry out this function as is exemplified in a conceptual tool proposed by Ma et al. [2003] which analyses the implications of a change in terms of the lead-times, design cost and resources associated with making the change. There are other approaches to assessing the consequences of a change, such as estimating the risk associated with making a change [Clarkson et al., 2001]. These types of numerical rating are intended to support designers and managers with decision making while creating change implementation process plans. However, they do not necessarily assist in drawing attention to possible propagation paths, which may result from making a change. As a result, they do not predict how changes propagate between parts of products.

The second object in change prediction is *identifying* the parts of a product that may be affected when making a change. This enables designers and managers to carry out a type of "what-if" analysis on proposed change alternatives. Thus instances where change propagates unexpectedly can be minimised. Eckert et al. [2005] explain that exhaustive and deterministic predictions are not practical due to many sources of uncertainty in design such as the choices that designers make. Tools provide estimates of possible propagation paths often derived from are assessments of product properties and relations. Products can be described from numerous view points, such as attributes, behaviours, functions, components, parameters, features and so on, depending on the nature of query. An example of a tool, which predicts possible propagation paths between components, is RedesignIT. This has been shown to support change prediction by analysis of causal process underlying the *behaviour* of a system [Ollinger and Stahovich 2004]. Other methods include analysis based on *structural* relations between components as used in the CPM tool [Clarkson et al., 2001], as well as *functions* as demonstrated by [Flanagan et al., 2003]. For each of the prediction tools reported, there have been studies that show that method of analysis have been sufficient for the purpose they were developed for. However, there are no studies that had critiqued the plausibility of the predicted estimates. Two main questions, which arise as a result of the different methods, are:

1. Is the prediction of change propagation paths based of one type of product relation (e.g. structural-relations) just as plausible as that based on another type of product relation (e.g. behavioural-relations) for the same change instance?
2. Are there any benefits to considering more than one type of product relation for assessing the possible change propagation patterns in products?

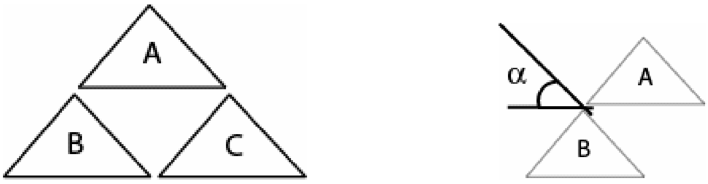
3. Product relations as cues for predicting change impact

There are different types of relations between parts of a product used in everyday engineering discourse. Design artefacts are generally intended to carry out *function*, which are satisfied using physical forms of with a specific *structure.* The interactions between parts, which constitute the product structure, yield observable *behaviours.* The descriptions of component interactions and relations can be in the form of structure, functions or behaviours. All three types of product relations are used independently as ways of identifying possible paths in which a change may propagate.

In the literature on change prediction, it is generally assumed that a product can be described as a set of objects that stand in some causal interactions. The basic principle of change prediction reported in design literature is through analysis of potential failure-states deducible from the interactions within an artefact. There are other approaches, such as the use of statistical estimates derived from historical cases of changes, which are used in software design but not yet to be used in engineering design. The scope of this study is limited to prediction cues derived from interactions within the product.

3.1 Structural relations as cues for prediction

The structure of a product is the relation between its parts at a chosen level of abstraction. The degree of connectivity between parts in a structure depends on the architecture chosen for the product. Models for representing structural relations describe parts of a product with reference to other parts. An example of a structural relation is illustrated in the diagram in Figure 1(b). Similarly, interactions such as patterns of heat-flow between an engine and the body of a car would depend on factors like the location engine. Patterns of interactions within a complex product are often constrained by the existing product architecture on which change is initiated. Often when a device fails to satisfy design goals, solutions are sought through modification of the structure. Changes to the structure of a component imply that some relations between components may no longer apply and in the same way, new relations may be introduced. To this end, assessment of the effects of a change based on component connectivity is likely to indicate which parts within the structure that changes are likely to affect.



a) b)

Figure 1. (a) System of three components A, B and C. (b) Structural relation between A and B

3.2 Functional relations as cues for prediction

Components are also related through functions. In the domain of engineering design, functions serve to communicate the intent of design engineers [Kirschman and Fadel 1998] however there are drawbacks associated with describing product functions. Methods for modelling products in terms of functions have been frequently described in various academic texts. Yet, since there are no specific methods that clearly separate a designer's intent from its implications, the usage of the term enables descriptions, which have a wide range of meanings. For example, the function of a thermostat may be to maintain an engine’s temperature or to prevent overheating.

Due to limitations that arise from the inconsistent descriptions for functions, there can be problems associated with using functions as a cue for predicting patterns of change propagation [Flanagan et al., 2003]. In order to overcome this limitation, Chandrasekaran [1994] explains that its beneficial to abstract in terms of the functional-role played by constituent components. A description of products in terms functionally related components enables mapping of relevant functions to object descriptions. Parts of a product are functionally related if the interactions contribute to achieving a functional goal. In practice, a component may have more than one function, as design engineers often promote function-sharing in components where possible. As a result, a component may belong to more than one system in a product. A change to a component to improve properties within one system can affect the performance of the same component within other systems. Evaluation of change to products in reference to functionally related components provides useful cues as to how changes may propagate.

a) b)

Figure 2. (a) System of three components A, B and C. (b) Abstract representation of functional relation between A, B and C

3.3 Behavioural relations as cues for prediction

The third type of interaction between components concerns how a device interacts with its environment. Products are characterised by behaviours that arise from the interactions between components. Figure 3 shows an abstract example of behavioural relations between entities. The resultant triangle in Figure 3(b) is not a property of any one of the constituent shapes alone. Similarly, product behaviour such as heat generated within an engine is not a property of the piston but an emergent property of the component interactions. Changes are made to a product in order that design engineers may match the product's behaviour to new requirements. It is important that the attained desired behaviour is maintained, while unavoidable undesired behaviour (such as vibrations) is kept within tolerable limits. Undesirable behaviours may lead to changes propagating between components. Patterns of change propagation can sometimes be dependent on the components associated with a particular behaviour.

a) b)

Figure 3. (a) System of three components A, B and C. (b) Emergent behaviour of A, B and C

Behaviours are essentially different from function in that behaviours can either be desirable or not. However, like functions there are drawbacks associated with representing product behaviours in that most descriptions can be subjective and inconsistent. Depending on the type of behaviour, product parameters such as vibration frequency and heat dissipation rates provide an indication of the extent to which a product exhibits certain behaviour. Thus, assessments of change instances based on relevant parameters enables estimates of possible propagation paths between entities associated with such parameters.

4. An example of change impact analysis

In order to assess how a type of product-relation may impact upon the plausibility of predicted propagation paths derived using a prediction tool, analysis of change scenarios were carried out based upon a previous extensive case study of change processes in a leading UK automotive company [Jarratt et al., 2004]. A model of a diesel engine developed with 7 engineers, containing 41 components, was reused to determine relevant connections between components in the engine. The analysis was carried out primarily to determine if there were any benefits in considering more than one type of prediction cue while assessing change impact. The CPM tool was used to analyse the structural relations between the components represented in the model. The tool was chosen because it had been shown to be helpful in predicting effects of change based on the same model used for this study within an industrial environment.

4.1 Brief description of CPM tool

The CPM tool enables analysis of possible propagation paths based on risk measures of changes propagating. The risk involved in carrying out a change is based on estimates of the likelihood, as well as the impact of a change propagating between one component to another. Predicted estimates are based on the assumption that a change can only propagate through direct connections, so that indirect risk can be calculated through direct connections. Brute force algorithms are used to calculate combined risk values of changes propagating between components.

Products are represented in the CPM tool using component breakdowns at a high level of granularity. A change DSM is used to capture any type of change causing relation between a pair of components according to the product structure. This type of component DSM is not symmetrical, as change propagation can be directional. Regardless of the reason for a change to propagate, cues about possible propagation paths are derived from *structural relations* between components. Consequently, assessments of possible propagation paths are limited to structurally related components only.

4.2 Analysing engineering change cases

This study looks at multiple changes to the oil filter of a diesel engine. While previous work only considered one change affecting a component, we now investigate the effects of several changes to one component. As a result, thorough descriptions of the oil filter's functionality are provided.

A typical oil filter consists of a pleated filtering element within a cartridge held in a casing containing a couple of valves as shown in Figure 4(b). Its main functions are (1) removal of contaminants such as burnt metal particulates and fluids introduced into the engine's lubrication oil during operation, (2) prevent contaminants from reaching sensitive parts of the engine while (3) allowing flow of oil to parts of the engine where lubrication is required. It is not always possible to fully satisfy functional-requirements (2) and (3) above. Thus, filters are fitted with bypass valves, which allow contaminated oil back into the engine to prevent oil starvation when filtration is slow or when the filter clogs up. Using an inefficient and/or inappropriate oil filter in an engine may lead to a reduced engine performance due to low effectiveness of lubrication oil; it could also lead to increased fuel consumption from inefficient lubrication. The appropriate oil filter for particular engine design may vary with different working conditions.

In terms of change, the oil filter is a functional part of the engine. Unanticipated effects of change to the filter may necessitate further changes to unintended components. [Jarratt 2004] described an instance in a UK company where changes to filter design from a regular commodity filter to a totally disposable filter with no metal liners lead to changes propagating within the engine.

The oil filter is not a core part of the engine. It is important that modifications to the oil filter, which may lead to propagation of changes to key components such as the engine block, be avoided. Identifying the possible effects of changes to the oil filter enables designers to seek alternative solutions in an attempt to meet design requirements.

4.2.1 Background of problem

In the automotive industry, it is common practice to use the same engine on a variety of cars. Diesel engines such as the model used for this analysis are designed for use in number off-road vehicles such as illustrated in Figure 4(a). The architecture of engines is modular in the sense that it has interfaces that fit into different vehicles. However, installing an engine into a new vehicle is not just a simple case of inserting a new module. There is often considerable amount adaptive work necessary due to the requirements of such vehicles. For example, the oil sump of many modern agricultural tractors are designed to withstand significantly higher stresses than is required for many other vehicles which operate on the same engine design. This is because the sump is a key structural member linking the front wheels to the rest of the vehicle. Similarly, the requirements for oil filters vary with different spatial constraints as well as working requirements and environments. Depending on the nature of the change problem, changes to an oil filter may cause changes to propagate in different ways.

a) b)

Figure 4. (a) Applications of a one engine model (b) Oil filter cutaway

4.2.2 Example scenarios

As a way of assessing the plausibility of prediction estimates derived from methods in which structural relations are used as cues for possible propagation paths, two hypothetical design changes to an oil filter were considered. The first case analysed the implications of increasing the size of the oil filter. Engines, which are required in harsh working conditions, may require oil filters with an improved filtering efficiency and filtering capability beyond the requirements for a standard engine. In order to achieve this, filter element surface-area may be increased. This change impacts the spatial requirements for the oil filter. It was assumed during this analysis that there is enough margins between components to absorb other side effects.

The second scenario analysed the implications of a change to the oil filter from a single to a two-filter system. In many vehicles, the oil filter is not easily accessible during engine maintenance. Consequently, it is beneficial if the oil filter replacement life exceeds the estimated lubrication oil life. Most modern engines are designed such that its oil filters have to be changed each time lubrication oil is changed. The introduction of the secondary filter significantly increases the duration for oil filter change. For the purpose of the analysis such change to the filter, two assumptions were made. First, it was assumed that both filters would be fastened to the engine with a single elbow to reduce possibilities of pipe leaks. Second, the strength of the coupling between the filter and the engine was within the margins of the elbow. There are three main implications of such changes. (1) An increase in the spatial requirements in the vehicle for oil filters, (2) a significant pressure drop across the inlet and outlet of both filters and (3) a notable increase in the average oil working temperature.

4.2.3 Description of analysis procedure

In order to analyse possible propagation paths in the two change scenarios considered a model containing structural, functional and behavioural relations between components was created. Following the completion of the model, each change case was assessed with respect to the different type of prediction cues to determine possible propagation paths. The component breakdown and the structural relations between them were already identified as a part of the original study on which these assessments are based. As a result, only functional and behavioural relations between components were added to the model for this analysis.

The first part of the model building procedure was identification of functionally related components. All 41 components were grouped into systems represented in the columns of a matrix. There were 9 systems in total including ignition, lubrication and cooling systems. Due to function sharing in engine design, a component may be part of one or more systems. Change to a component may only propagate to other components, which are functionally related to it – either within a system or in another system that shares one or more constituent component.

Similarly, for the second part of the model building process, a matrix was used to identify components associated with a particular behaviour. Product parameters such as oil flow rate were used to represent the behaviour arising from component interactions. However, although there are many possible parameters associated with one component, only parameters relevant to each change case were considered. Change may only propagate between components associated by a particular behaviour.

4.3 Plausibility of predicted estimates

In both the change cases examined, three sets of analysis were carried out using structural, functional and behavioural relations respectively as cues for identifying possible propagation paths. It was observed that the predicted propagation paths were different for each of type of analysis and the plausibility of each was dependent on the nature of the initial change. The results show that there are benefits to analysing change cases against different types of change relations.

4.3.1 Change analysis based on structural relations

Assessments of change to the oil filter based on structural relations within the engine were carried out using the CPM tool. In the first change case, the method enables estimation of risk associated with changes to the oil filter propagating to other parts of the engine as well as an analysis of propagation paths as illustrated Figure 5. Components such as the starter-motor, fuel filter and flywheel housing are identified as most likely components to be affected by a change the oil filter. These findings are plausible since these components are constrained by spatial relationships. However, there was no significant difference in the findings from the first change case and the second scenario. There are several explanations for this lack of difference but the primary reason was because the CPM tool uses cue derived from structural based estimates of propagation paths, which do not necessarily accommodate the contextual influence of the initial change.

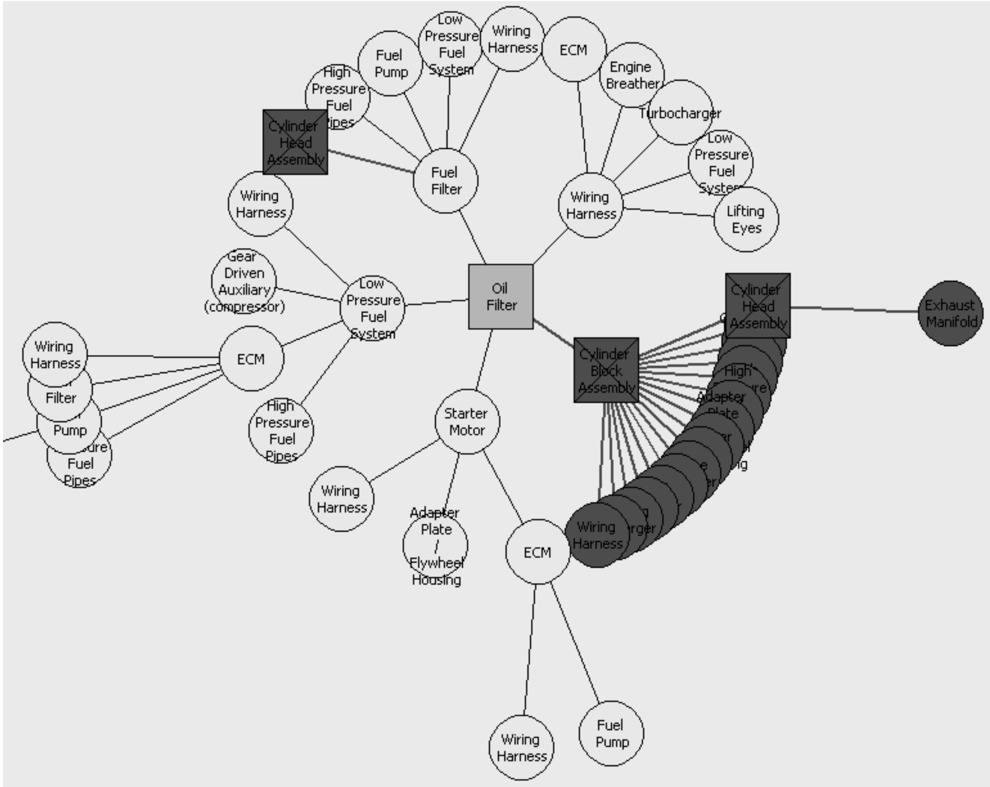


Figure 5. A propagation network for the "oil filter"

4.3.2 Change analysis based on functional relations

An assessment of propagation paths based on functional relations showed that changed will not propagate between functionally related components in the first case. However, in the second change scenario, it was noted that the change to the oil filter may cause an overheating of the engine oil. Such a change may propagate to one or more components functionally related to the oil filter, such as the lubrication oil itself or the oil cooler. For example, lubrication oil with greater viscosity may be used to reduce effective thinness of the oil at high temperature, or a more efficient oil cooler may be necessary to dissipate heat. This possible propagation path may not be picked upon when using a tool, which considers only the structural relations between components.

4.3.3. Change analysis based on behavioural relations

Again, an assessment of the first change case based on behavioural relations did not provide any clues to possible propagation paths. Perhaps, this is due to the assumptions on which the first example was based. However, the type of change proposed in the second example case may have resulted in nontrivial changes to the behaviour of the component interactions. An analysis based on behaviour would have drawn attention to other components within the engine such as the oil pump and oil-cooler, which are associated with oil flow behaviour. The type of change analysed in the second example scenario may have resulted in further changes within the engine, especially to the oil pump.

4.3.4 Observations

Estimates of possible propagation paths varied according to the prediction cues used. For example when the possible propagation paths resulting from a change were assessed against structurally related cues, components that do not contribute to lubrication in anyway such as the starter motor and fuel filter were identified as the most likely propagation paths. However, when the same analysis was based on functional relations, components such as the oil cooler were identified.

It is important to note that a pair of component may be related by more than one type of relation at a time, for example the oil filter and oil cooler were related functionally as well as through behaviour. As a result, estimates of propagation paths based on different relations may be similar. However, each of the three types of relationships is essentially different, hence causing change to propagate differently. For example, the components that contribute to perceived behaviour such as an engine's legacy properties might not be functionally related. As a result, an assessment based on behaviour will propagate different to that based on functional related components. Also, analysis of possible propagation paths based on function can determine possibilities of change propagation between systems, which may not be picked up on when assessing propagation paths based on behaviours.

5. Discussion

It is not possible to predict the outcomes of change effects exhaustively and deterministically. Yet, there is a need for methods to generate plausible estimates of how changes propagate. It can be seen from the findings from the literature as well as the analysis carried out that plausibility of predicted estimates depend on the relative "richness" of the data used to carry out predictions. Inferences derived from sparse data can be relatively incomplete and misleading. A more complete model of component relations such as that used to analyse cases of change to an oil filter required more effort to build but yielded better results. Effectively, there is a trade-off between the effort required in building the model and the accuracy of predictions.

Owing to the number of possibilities for change propagation, product relations can be used as cues for pruning the number of possible propagation paths when assessing the effect of a change. Structural, functional and behavioural relations are identified as mechanism through which changes may propagate. They also serve as useful cues for supporting change prediction. Although, there are a few prediction tools for estimating possible propagation paths, they are all based on only one of the different types of change relations (for example the CPM tool). The plausibility of predicted estimates is likely to be greater when all three types of relations are considered during change impact evaluation. Sometimes, a pair of components may interact with two or more types of relations (e.g. structure as well as function). This does not mean that both types of relations are the same. Analysis based on any combination of these component relations may not be as effective as in a case where all the different relations are considered.

6. Conclusions and further work

In this paper, we review recent work on change prediction methods. In addition to factors which limit predictability (such as uncertainty in the design process) the type of prediction cues used to support change prediction affects the accuracy of predicted estimates. The use of a more complete model that accommodates different types of component interactions is identified as crucial step towards generating better estimates of how a change may propagate. It is argued that change will propagate between components if:

- the product does not attain the required behaviour
- there are insufficient margins to accommodate effects of changes to structural interactions
- the product does not satisfy intended functions

Analysis of changes made to an oil filter using the CPM tool was used to support the argument that estimates based on structurally related components alone may not be as complete as analyses where all three types of product relations are considered.

Ultimately, the path through which a change propagates within a product is not only dependent on relations between constituent components. As a result, further work is required to assess the implications of process issues, such as manufacturing capabilities, on how changes propagate. The analysis reported in this paper provides a theoretical basis on which change propagation prediction methods can be developed. This forms part of an ongoing research into attaining plausible estimates of change propagation during change impact analysis.

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