INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

A FUNCTIONAL ANALYSIS OF CHANGE PROPAGATION

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Abstract

A thorough understanding of change propagation is fundamental to effective change management during product redesign. A new model of change propagation, as a result of the interaction of form and function is presented and used to develop an analysis method that determines how change is likely to propagate. The analysis produces a Design Structure Matrix, which clearly illustrates change propagation paths and highlights connections that could otherwise be ignored. This provides the user with an in-depth knowledge of product connectivity, which has the potential to support the design process and reduce the product's susceptibility to future change.

Keywords: design structure matrix, complexity, change process, variant management

1 Introduction

Redesign is common; companies frequently modify their products and rarely start from scratch when designing [1]. Modifications occur for a variety of reasons including: customer requests, new requirements and legislation, error correction, proactive adaptation to improve design quality, and unforeseen changes required to remove undesirable characteristics.

Many companies regard the changes associated with redesign as a major problem source [2, 3]. Product redesign is often considered an interruption rather than an opportunity for product enhancement. Change processes are frequently mismanaged [4]. This can result in change avalanches [5] which are extremely costly to companies. Not every unexpected propagation produces an avalanche, but many alterations cause problems or require additional work. Designers are overwhelmed by the complexity of the product and do not properly understand how changes affect each other. In this environment, guidance on change management is essential. There are many issues that such guidance should address, the most critical of which are considered below.

The designer is often unaware of the consequences of a particular change. Such knowledge would give a feel for the total redesign cost of the change, and an idea of what else is likely to need modification, thus facilitating better change management. When a new product is created by modification from an existing one, this method gives an opportunity to reduce the product's total susceptibility to future change propagation. Companies can apply different strategies (see also [6, 7]):

- build change resistant product architecture: common core module, clearly defined interfaces, modular architecture, minimum number of functions per component [8];
- manage tolerance margins in design [9];
- avoid mistakes and use better processes.

All of these methods require an understanding of change propagation. Current models of change consider a-priori connectivity (e.g. [10]) or analyse the change by considering component interaction [11]. The method discussed in this paper explicitly models change paths by considering propagation through functional connections. This allows the designer to predict the consequences of a particular change, thus reducing susceptibility to change and facilitating effective change management.

2 A Component – Function Propagation Method

This section provides an overview of the method and the assumptions behind it. The details are explained using an example in the following section.

2.1 Form-Function Interaction

Change is often considered in terms of either form or function. However, all engineering design involves both; there is no form without function and no function without physical manifestation. Further, it is the interaction of both attributes that causes change propagation [12]. A change to functional requirements necessitates a change in form to achieve the new functionality. This change in form may, in turn, result in a subsequent functional change. Such interaction of function and form allows causes change to propagate through the design.

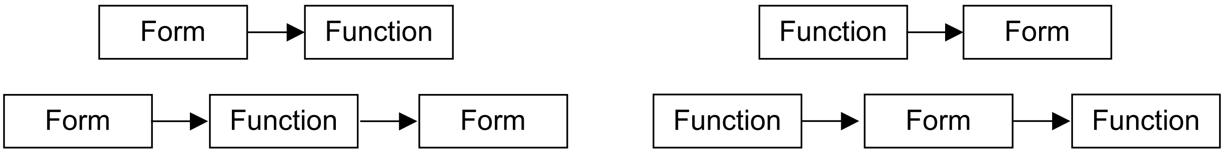


Figure 1. Types of change propagation

Two components (forms) can only affect each other if there is a functional link between them. Otherwise, there is no reason why a change to one function would cause a change to another. In some cases, however, it is difficult to think in terms of functions and this vital link is ignored.

2.2 Assumptions

Built on the above argument, a method for describing and analysing change propagation has been developed. The method makes use of the designer's understanding of the functionality of the product to generate a matrix showing the connectivity between different features of the design. In this paper, the term feature is used exclusively for component–function pairs, for example the features of a bolt which provide grip.

The method makes the following assumptions:

- Functions can be described independently and at an even level of detail;
- An unambiguous component breakdown on an even level of a detail can be generated;
- The function and component breakdowns match; and
- Changes are carried out in a rational way; i.e. changes are only made where necessary

2.3 Overview of the Method

An overview of the method is given in Figure 2. The user is asked to generate both a functional breakdown and a component breakdown of the system. This can involve considerable effort, because care must be taken to ensure that the components are described clearly and that components which link two subsystems together are assigned to one of these subsystem. Using these breakdowns the user must provide a function – function and a component – component matrix in the familiar form of Design Structure Matrices [13, 14], which could themselves be subjected to probabilistic component-component propagation techniques such as those described by Jarratt [11]. The user must also provide a component – function matrix showing which components and functions are connected. From these, the system generates a matrix showing which component-functions pairs (features) are connected. Rewriting this matrix, the tool can show the propagation paths between these features, thus providing an analysis of how change spreads through the system.

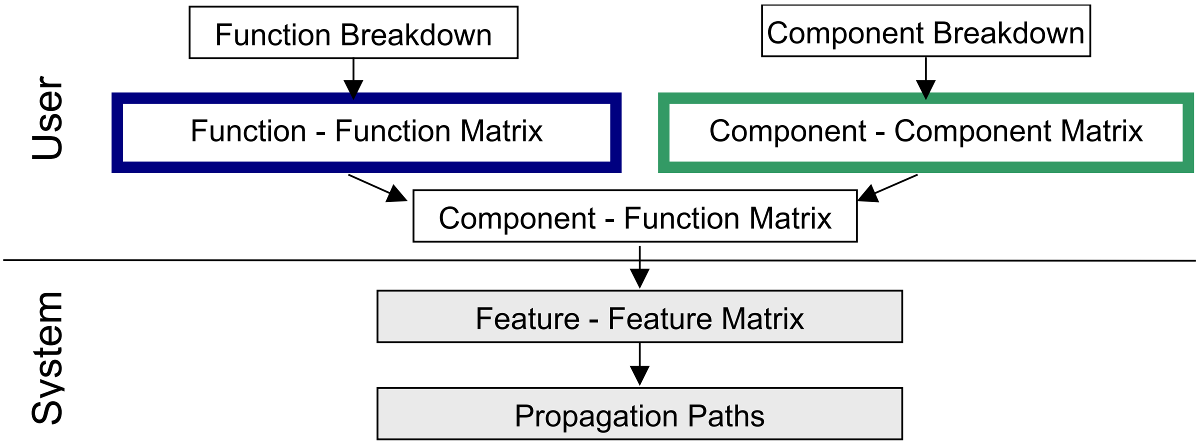


Figure 2. Overview of the Method

3 Case study

This section goes through the steps of the method, as outlined in Figure 2, using the front shovelling mechanism of a mechanical digger in order to demonstrate how the method can be applied.

3.1 Creating component-component and function-function matrices

The method begins with a functional breakdown of the product. These functions should be independent and on the same level of detail. Further, they should reflect design requirements since these often provide a useful way to think about functions. However, one must remember that not all requirements are functional.

The key functions of the digger are to:

- Carry load – the structure must carry the applied load;
- Raise load – the mechanism must lift the load to a height suitable for dumping;
- Shunt – the bucket geometry must be suitable for moving and containing load;
- Tilt – the mechanism must achieve bucket tilt suitable for dumping.

The components which carry out these functions are the bucket, the bucket link, the bucket hydraulics, the arms, the arm hydraulics and the hydraulic pipes (Fig. 3).

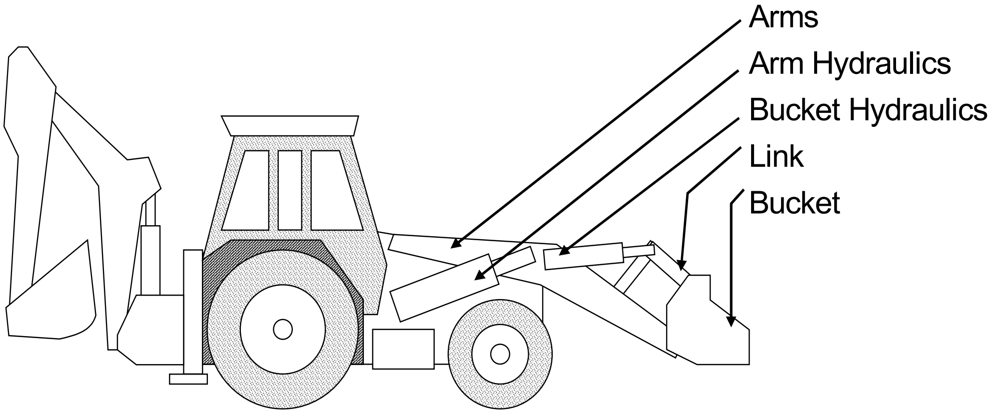


Figure 3. The Digger

These functions and components are used to build the function-function and component-component matrices below (Fig. 4). An X represents connectivity between a component-component pair or a function-function pair. The component-component pair is inherently symmetric as it represents the physical connectivity between components, e.g. A is bolted to B. The function-function matrix is built by considering whether a change to one function will result in a change to another. For example the shunt and carry load functions are connected, as a change that results in a stronger digger will allow shunting and carrying of greater loads. Functional matrices are not necessarily symmetric, though they can be (as in this example).

	Bucket	Arms	Arm Hydraulics	Bucket Hydraulics	Hydraulic Pipes	Bucket Link
Bucket	▨	X		X		X
Arms	X	▨	X	X	X	X
Arm Hydraulics		X	▨		X	
Bucket Hydraulics	X	X		▨	X	X
Hydraulic Pipes		X	X	X	▨	
Bucket Link	X	X		X		▨

	Shunt	Raise Load	Carry Load	Tilt
Shunt	▨		X	X
Raise Load		▨	X	
Carry Load	X	X	▨	X
Tilt	X		X	▨

Figure 4. Component-Component Matrix and Function-Function Matrix

3.2 Building the component-function matrix

The last step for the user involves building the component-function matrix and identifying which components and functions are connected. Essentially, this involves asking oneself a series of questions of the following form: is component X involved in carrying out function Y?" If a connection exists between a function-component pair, a letter is used to represent this connection (Fig. 5). Thus, the letter A refers to the shunting features of the bucket.

	Bucket	Arms	Arm Hydraulics	Bucket Hydraulics	Hydraulic Pipes	Bucket Link
Shunt	A	B		C		D
Raise Load		E	F			
Carry Load	G	H	I	J	K	L
Tilt	M	N		O		P

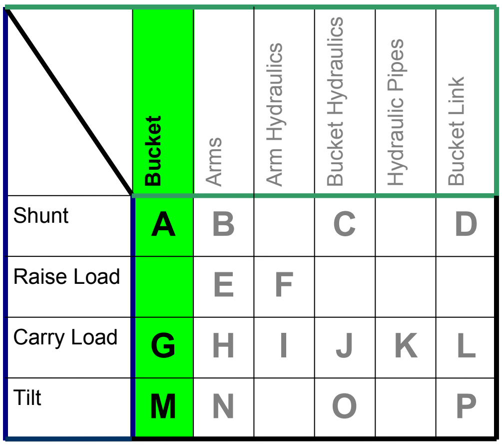
Figure 5. Component-Function Matrix

Features can be thought of as aspects of a particular component that carry out particular functions. For example, some features of the bucket are involved in the shunting function and others contribute towards the load carrying function. By considering features rather than entire components a more complete understanding of change propagation is possible. One sees not only which components are connected but also which aspects of a given component cause these connections. Some components are connected in more than one way. For example, the arms and the bucket are linked by three functions: shunting, carrying load and tilting.

3.3 Generating the direct connectivity matrix

Connectivity between multiple features within one component

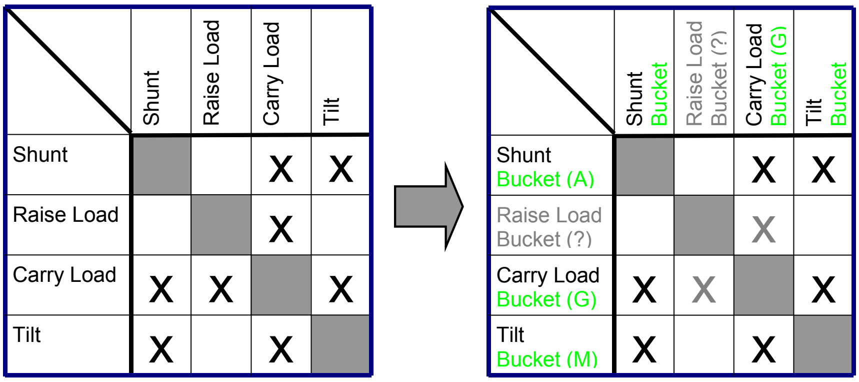
If a component has features addressing more than one function, and these functions are connected, then the different features of the component will also be linked through functionality. One component that demonstrates this connectivity is the bucket. Looking at the highlighted column of the component-function matrix, it can be seen that the bucket has features concerned with bucket shunt function (A), the load carrying function (G) and tilting function (M).



	Bucket	Arms	Arm Hydraulics	Bucket Hydraulics	Hydraulic Pipes	Bucket Link
Shunt	**A**	B		C		D
Raise Load		E	F			
Carry Load	**G**	H	I	J	K	L
Tilt	**M**	N		O		P

Figure 6. Component-Function Matrix

Information concerning functional interaction of these features is contained in the function-function matrix (Fig. 7). The second column of this matrix states that there is connectivity between shunt and load carrying functions and also between the shunt and tilt functions. A matrix can be built for the different features of the bucket (Fig 7). The connectivity between these features is due to function and hence can be determined by masking the component-function matrix (Fig. 6) over the function-function matrix (Fig. 7). This process filters the general connectivity between functions onto the specific case of the bucket.



	Shunt	Raise Load	Carry Load	Tilt
Shunt	▨		X	X
Raise Load		▨	X	
Carry Load	X	X	▨	X
Tilt	X		X	▨

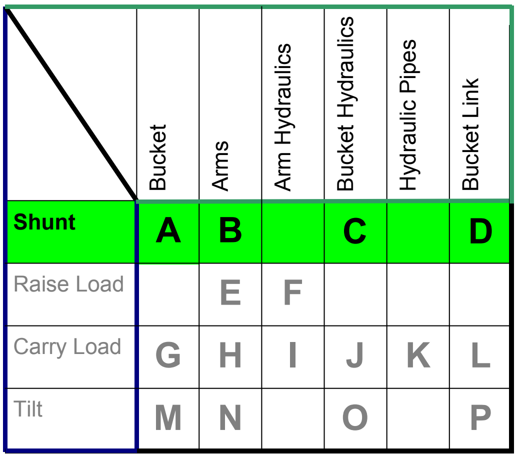
	Shunt Bucket	Raise Load Bucket (?)	Carry Load Bucket (G)	Tilt Bucket
Shunt Bucket (A)	▨		X	X
Raise Load Bucket (?)		▨	X	
Carry Load Bucket (G)	X	X	▨	X
Tilt Bucket (M)	X		X	▨

Figure 7. Function-Function Matrix and Bucket Features Matrix

The raise load/bucket combination is shown in faint grey and identified with a question mark because the bucket does not have features that address the load raising function. Nevertheless, the feature is included to simplify mapping of the matrices by keeping the shape consistent. The masking process described here for the bucket must also be performed for the other components. By considering each component in turn, the functional links within every component can be identified.

Connectivity between components

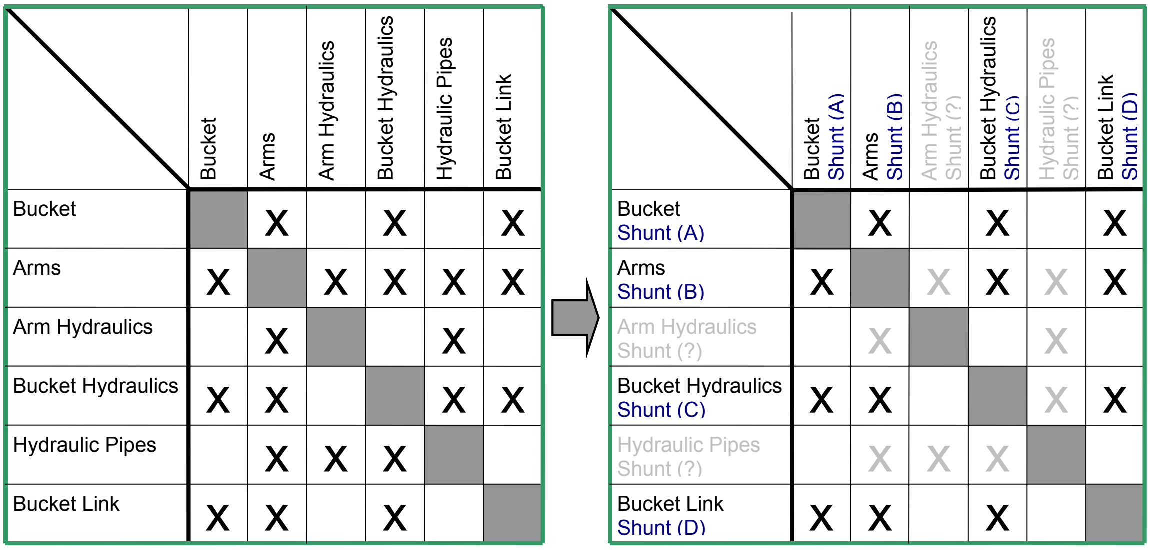
Connectivity may also occur if different components combine to perform the same function. The component-function matrix shows which components combine together to perform a given function (Fig. 8). The highlighted column of the matrix shows that the bucket (A), the arms (B), the bucket hydraulics (C) and the bucket link (D) are all connected by the shunt function.



	Bucket	Arms	Arm Hydraulics	Bucket Hydraulics	Hydraulic Pipes	Bucket Link
Shunt	A	B		C		D
Raise Load		E	F			
Carry Load	G	H	I	J	K	L
Tilt	M	N		O		P

Figure 8. Component-Function Matrix

The component-function matrix shows which components perform a given function, but cannot be used to determine how the components interact to achieve this functionality. For example, the bucket link mechanism and the arm hydraulics are both involved in the load carrying function but these components are not directly connected to each other. Information about which components are connected is contained in the component-component matrix. Thus, by masking the component-component matrix over the component-function matrix, the direct connectivity of different components that perform a common function can be found. Masking the first column of the component-function matrix over the component-component matrix relates the different features connected by the shunt function as shown in Fig 9.



	Bucket	Arms	Arm Hydraulics	Bucket Hydraulics	Hydraulic Pipes	Bucket Link
Bucket	▨	X		X		X
Arms	X	▨	X	X	X	X
Arm Hydraulics		X	▨		X	
Bucket Hydraulics	X	X		▨	X	X
Hydraulic Pipes		X	X	X	▨	
Bucket Link	X	X		X		▨

	Bucket Shunt (A)	Arms Shunt (B)	Arm Hydraulics Shunt (?)	Bucket Hydraulics Shunt (C)	Hydraulic Pipes Shunt (?)	Bucket Link Shunt (D)
Bucket Shunt (A)	▨	X		X		X
Arms Shunt (B)	X	▨	X	X	X	X
Arm Hydraulics Shunt (?)		X	▨		X	
Bucket Hydraulics Shunt (C)	X	X		▨	X	X
Hydraulic Pipes Shunt (?)		X	X	X	▨	
Bucket Link Shunt (D)	X	X		X		▨

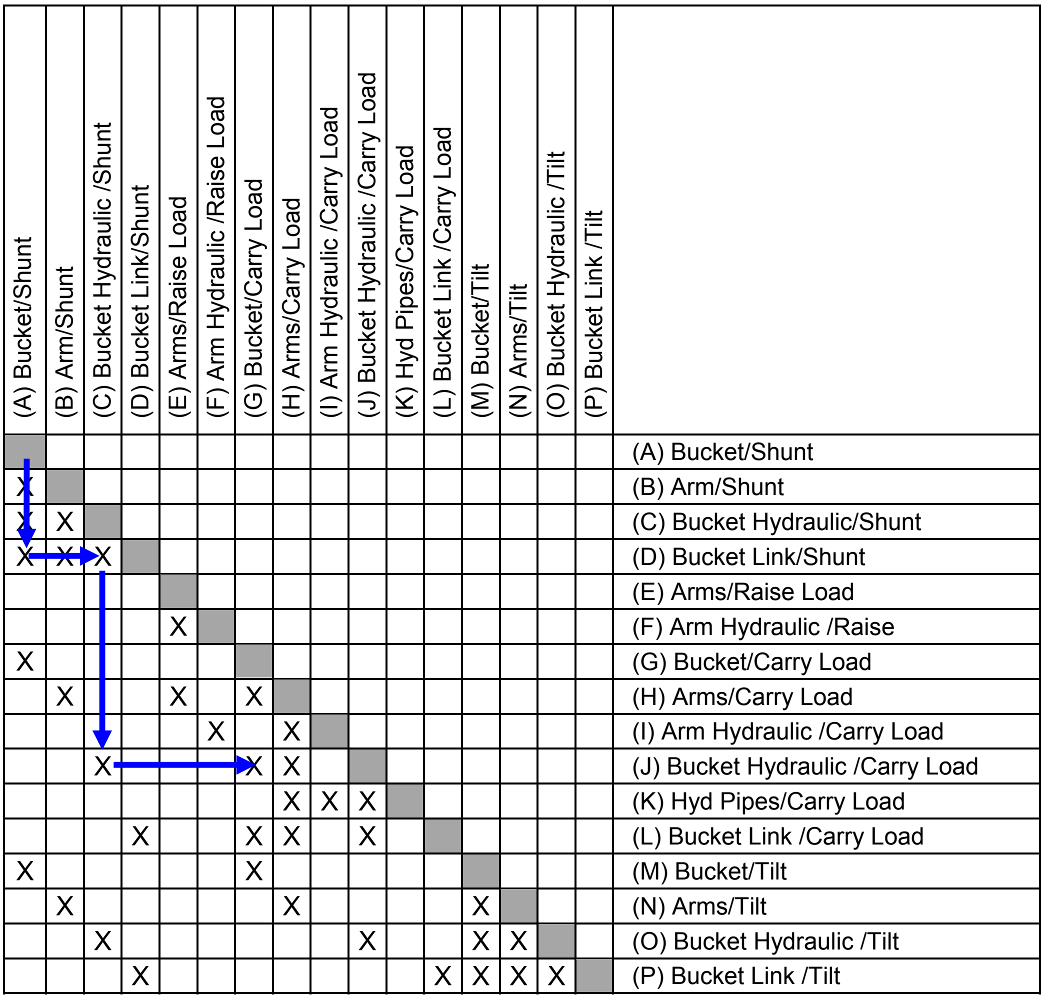
Figure 9. Component-Component Matrix and Shunting Features Matrix

The first row of the shunting features matrix (Fig 9) represents connectivity between the shunt features of the bucket (A) and the shunt features of the arms (B). The bucket is also connected to the bucket hydraulics and the bucket link by the shunt function. The arm hydraulics and the hydraulic pipes are not involved in the shunting function but have been included in figure 9 for completeness. Looking at figure 9, it can be seen that the arms (B) are related to the bucket hydraulics (C) and the bucket link (D) through the shunting function. However, the arms are not connected to either the arm hydraulics or the hydraulic pipes by the shunting function.

The masking process described here for the shunt function must also be performed for the other functions. By considering each function that involves multiple components working together in turn, the functional links between features of different components can be identified. It is worth noting that multiple links between two components are possible, in cases where the same component performs more than one function. For example, both the raise load and the carry load functions link the arms to the arm hydraulics. However, multiple links between features can not occur.

The direct connectivity matrix

By considering the connectivity between components due to shared functionality and connectivity between different features of the same components, an overall picture of connectivity for the different feature of the product is obtained (Fig 10). This connectivity matrix has been automatically generated by a computer program which takes the component-component, function-function and component-function matrices as inputs.



(A) Bucket/Shunt	(B) Arm/Shunt	(C) Bucket Hydraulic /Shunt	(D) Bucket Link/Shunt	(E) Arms/Raise Load	(F) Arm Hydraulic /Raise Load	(G) Bucket/Carry Load	(H) Arms/Carry Load	(I) Arm Hydraulic /Carry Load	(J) Bucket Hydraulic /Carry Load	(K) Hyd Pipes/Carry Load	(L) Bucket Link /Carry Load	(M) Bucket/Tilt	(N) Arms/Tilt	(O) Bucket Hydraulic /Tilt	(P) Bucket Link /Tilt	
▨																(A) Bucket/Shunt
X	▨															(B) Arm/Shunt
X	X	▨														(C) Bucket Hydraulic/Shunt
X	X	X	▨													(D) Bucket Link/Shunt
				▨												(E) Arms/Raise Load
				X	▨											(F) Arm Hydraulic /Raise
X						▨										(G) Bucket/Carry Load
	X			X		X	▨									(H) Arms/Carry Load
					X		X	▨								(I) Arm Hydraulic /Carry Load
		X				X	X		▨							(J) Bucket Hydraulic /Carry Load
							X	X	X	▨						(K) Hyd Pipes/Carry Load
			X			X	X		X		▨					(L) Bucket Link /Carry Load
X						X						▨				(M) Bucket/Tilt
	X						X					X	▨			(N) Arms/Tilt
		X							X			X	X	▨		(O) Bucket Hydraulic /Tilt
			X								X	X	X	X	▨	(P) Bucket Link /Tilt

Figure 10. Feature-Feature Direct Connectivity Matrix

4 Change propagation paths

The direct connectivity matrix (Fig. 10) can be used to identify the change propagation paths between different features of the design. Figure 10 shows the connections between the shunt features of the bucket and the load carrying features of the bucket hydraulics. The propagation as shown takes the following path: A, D, C, J, G. The links between A and D and between D and C are due to common function of shunting. C is linked to J because both shunting and carrying load functions influence the design of the bucket hydraulics. J and G are linked by the load carrying function.. The propagation paths for all design features can be determined automatically, but this data is not included here due to space consideration.

The theoretical maximum number of possible change propagation paths for all possible initiating changes, is a factorial function of the number of features considered, for a fully populated matrix. Hence, the results become overwhelming and meaningless if all paths are considered. However, the number of possible paths can be reduced to a meaningful value by allowing the user to specify precedence relationships between components, for any envisaged change.

If the designer knows that he will always change the bucket and not the arms in cases where either change will suffice, many change propagation paths disappear. Such may be the case if a component is supplied from a subcontractor or if a component is used in multiple designs.

Project planning information from techniques such as signposting [15] or design structure matrices [13, 14] could also be used to reduce the number of propagation paths by creating an order of precedence between tasks. Components which are designed early in the project are less likely to change than those designed during later tasks as designers are keen to avoid rework where possible.

The routes can be queried by the user (Fig. 11), who might be interested in a particular connection. The user can also evaluate the validity of certain links in the context of the proposed modification. The model thus produces a set of results suitable for use in change management.

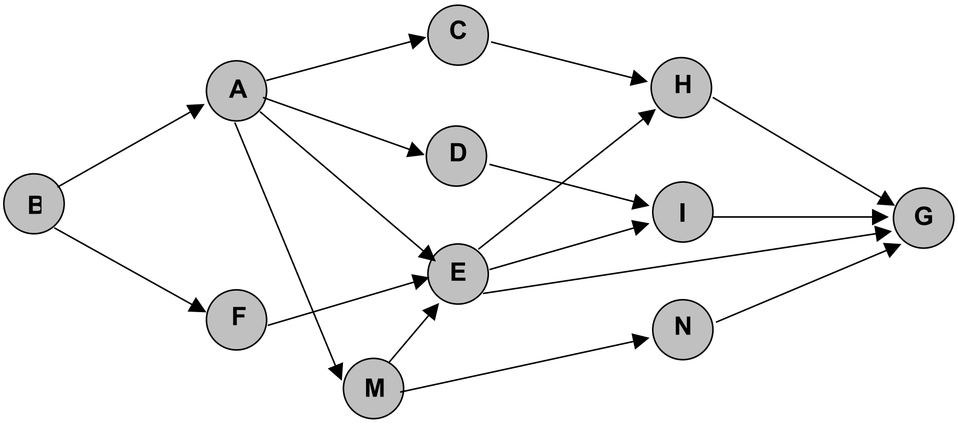


Figure 11. Change tree diagram

6 Conclusions

This paper introduces a novel method for describing and predicting how change can propagate through the link between functions and components. It brings out many indirect links that would otherwise be easily ignored, thus providing the user with an in depth knowledge of product connectivity, which supports the efficiency of design processes especially in design communication [16]. The method can be extended to include a probabilistic analysis by considering the probability of individual feature links to spread the change. This will make the method a useful tool for risk assessment. We are also working on providing a computer support environment that will help the user to think about function and form in a systematic way and visualise connectivities and propagation paths [17].

Acknowledgements

The authors wish to thank the UK Engineering and Physical Sciences Research Council (grant GR/R64100/01) for funding this research.

References

[1] Cross N., "Engineering Design Methods", John Wiley and Sons, Chichester, 1989.

[2] Acar B.S., Benedetto-Neto H. and Wright I.C., "Design change: problem or opportunity" Engineering Design Conference, Brunel University, UK: Professional Engineering Publishing, 1998.

[3] Hsu T.C., “Causes and impacts of class one engineering changes: an exploratory study based on three defence acquisition programs”, in Department of Aeronautics and Astronautics, MIT, Boston, 1999, pp.153.

[4] Diprima, M., “Engineering change control implementation considerations”, Production and Inventory Management, Vol. 23, No. 1, 1982, pp.81-87.

[5] Eckert C.M., Zanker W. Clarkson P.J., “Aspects of a better understanding of changes”, Proceedings of ICED ’01, Glasgow, UK, 2001.

[6] Terwiesch C. and Loch C.H., “Managing the process of engineering change orders: the case of the climate control system in automobile development”, Journal of Product Innovation Management, Vol. 16, No. 2, 1999, pp.160 - 172.

[7] Fricke E. et al., “Coping with changes: causes, findings and strategies”, Systems Engineering, 2000, pp.169-179.

[8] Suh N., “Principles of Design”, Oxford University Press, Oxford, 1990.

[9] Eckert C.M., Zanker W. and Clarkson P.J., “Change customisation in complex engineering domains”, Research in Engineering Design, in press.

[10] Clarkson P.J., Simons C. and Eckert C.M., “Predicting change propagation in complex design”, Journal of Mechanical Design, in press.

[11] Jarratt T., Eckert C.M., Clarkson P.J. and Schwankl L., “Product architecture and the propagation of engineering change”, Proceedings of DESIGN 2002, 7th International Design Conference Dubrovnik, Croatia, The Design Society, 1, 2002, pp.75-80.

[12] Smith J., “A functional analysis of change propagation”, Cambridge EDC Technical Report, 2002.

[13] Steward D., “The design structure system: a method for managing the design of complex systems” IEEE Transactions on Engineering Management, Vol. EM-28, No. 3, 1981, pp. 71–74.

[14] Eppinger S. D., Whitney D. E., Smith R. P. and Gebala D. A. "A model-based method for organizing tasks in product development", Research in Engineering Design, 1994, pp.1-13.

[15] Melo A.F. and Clarkson P.J., “Design process planning using a state-action model,” Proceedings of ICED’01, Glasgow, UK, 2001.

[16] Marca D.A. and McGowan C.L. "IDEF0 - SADT Business Process and Enterprise Modelling", EMcGraw-Hill, 1993.

[17] Eckert C.M. and Clarkson P.J. “Connectivity as a key to supporting design”, Artificial Intelligence in Design, Cambridge, UK, 2002, pp.479-501.

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