Proceedings of the 21st International Conference on Engineering Design (ICED 17) Design Methods and Tools, 21-25 August 2017, Vancouver, Canada.
https://www.designsociety.org/publication/39673/predicting_and_visualizing_cost_propagation_due_to_engineering_design_changes

PREDICTING AND VISUALIZING COST PROPAGATION DUE TO ENGINEERING DESIGN CHANGES

Georgiades, Alex (1); Sharma, Sanjiv (2); Kipouros, Timoleon (1,3); Savill, Mark (1)
1: Cranfield University, United Kingdom; 2: Airbus, United Kingdom; 3: University of Cambridge, United Kingdom

Abstract

During product development changes in the initial design are ubiquitous. The ability to predict such changes, along with the expected costs, is a challenge on its own. This challenge increases exponentially when a single design change on one element of the system propagates to other components. As change propagates, so does the cost associated with it; where cost is more than just financial. A number of knowledge-based methods have been developed in the past that assist in the prediction of how change propagates through a system, and the impact that it can have on other components. None of the methods developed, however, considers how cost propagates due to design changes. This paper presents a novel methodology for predicting, visualizing, and assessing the propagation of change and the cost associated with it. As part of the methodology, a new method, CP2, has been developed to calculate the propagated costs. The methodology has been applied to a conceptual example of a simple system to demonstrate the procedure and the use of the methods. The visualization of the results arising from this methodology is also demonstrated as a mechanism for design decision-making.

Keywords: Design methodology, Design methods, Design costing, Visualisation, Decision making

Contact:
Alex Georgiades
Cranfield University
School of Aerospace Transport & Manufacturing
United Kingdom
a.georgiades@cranfield.ac.uk

1 INTRODUCTION

In the current age, where product development is driven by rapidly changing market requirements, design changes can occur at any point during the development of any system or product. As the development process moves on, the costs associated with any design change increase, sometimes, by a factor of 10 (Clark and Fujimoto, 1991; Anderson, 1997). This calls for an effective engineering design change management, defined as the process where design changes are managed and controlled (Kidd and Thompson, 2000).

Such design changes do not only affect the element of the system that needs to be redesigned but might also lead to changes to the whole system. This phenomenon, known as change propagation, has been a topic of interest, especially in engineering design, and substantial research has been undertaken to develop methods that can predict and manage change propagations. Clarkson and Eckert (2004) presented an overview of the methods. Further, Keller (2007), Hamraz, Caldwell and Clarkson (2013) compare and contrast many of these methods.

Change propagation becomes even more important when dealing with more complex systems especially in cases where elements, subsystems or components, are heterogeneously (tightly or loosely) coupled.

The ability to predict the propagation of design changes, and quantify their impacts, can assist in a better evaluation and sensitivity analysis of the system that is being designed. A number of methods and approaches have been developed in the past; an overview of which is presented in the next chapter. The limitation with the methods developed so far is that none of them considers the cost that is associated with change propagation. In their paper, Koh, Caldwell, and Clarkson (2013), do include cost in their methodology, but they only consider the cost of the final affected component. It does not consider how the cost is accumulated by the intermediate changes between the initiating and receiving components.

The novel methodology presented in this paper aims to introduce a new method, CP^2 (Cost Prediction for Change Propagation), for change propagation by taking cost into consideration, and employ appropriate visualization methods to further assist the decision making process. By building on existing change prediction methods, the proposed method assigns a cost weight to the elements of the system. When a design change is triggered, the change propagates but so do the costs.

A more thorough evaluation of the system's sensitivity to changes and the associated costs can be assessed by predicting the propagation of cost due to design changes. This will allow the identification, and possible isolation, of elements in a system that can cause significant rise in costs, if design changes were to occur. Even in cases where changes are unavoidable, CP^2 can provide decision-making information in order to manage change propagation, and make necessary provisions.

The terms *element* and *component* are used interchangeably in this paper; as are the terms *probability* and *likelihood.*

2 BACKGROUND ON CHANGE PROPAGATION AND PREDICTION

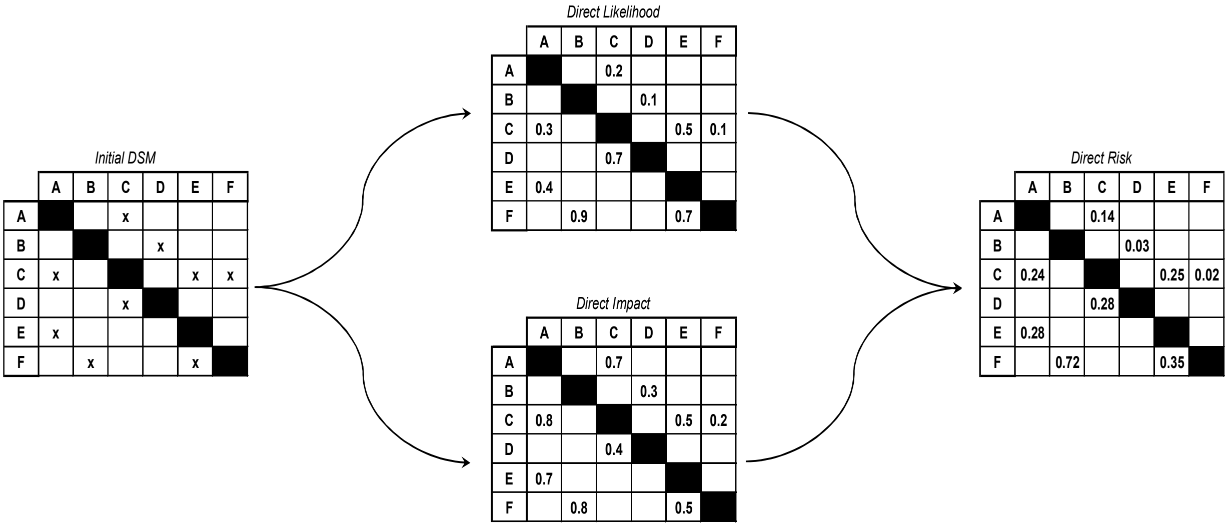
A number of different approaches have been developed in order to model change propagation, with C-FAR being one of the major ones (Cohen, Navathe and Fulton, 2000). It uses vectors to define the components and their attributes, with their characteristics as the vector elements, and then uses a matrix to capture dependencies amongst these characteristics. It starts by defining the propagation paths, then multiplies the change vector with the respective matrix, and then aggregates all possible paths. Since it is based on a large number of matrix and vector multiplications to calculate all possible propagation paths, especially in a large and complex system, makes this method slow and computationally expensive.

The other major approach for predicting design changes is CPM (Change Propagation Method), which makes use of Design Structure Matrices (DSM) (Clarkson, Simons and Eckert, 2004). A DSM succinctly represents the dependencies amongst the components of a system. It is essentially a square (NxN) matrix, where rows and columns represent the components of the system, and the cells inside the matrix are used to identify dependencies and connections between the components. It is widely used in engineering management for system decomposition (Browning, 2001) and for network modelling purposes (Eppinger and Browning, 2012).

In the case of CPM, a way to interpret the DSM is that for any connection in the matrix, the corresponding column is the component that triggers the change (transmitter), and the corresponding row is the component that receives the change (receiver).

CPM makes use of 3 main values: Likelihood, Impact and Risk (where Risk is the product of likelihood and impact). In order to calculate the change propagation, initially two quantified instances of the DSM are generated. One includes the value of how likely the change will propagate directly from one component to the other; the other DSM measures the impact of that design change on the receiving component.

All values of Likelihood, Impact and Risk are measured between 0 and 1 (sometimes expressed as a percentage). The values of direct Likelihood and Impact are obtained through experts' opinions and the risk is the product of the two values.



Initial DSM

	A	B	C	D	E	F
A	■		x			
B		■		x		
C	x		■		x	x
D			x	■		
E	x				■	
F		x			x	■

Direct Likelihood

	A	B	C	D	E	F
A	■		0.2			
B		■		0.1		
C	0.3		■		0.5	0.1
D			0.7	■		
E	0.4				■	
F		0.9			0.7	■

Direct Impact

	A	B	C	D	E	F
A	■		0.7			
B		■		0.3		
C	0.8		■		0.5	0.2
D			0.4	■		
E	0.7				■	
F		0.8			0.5	■

Direct Risk

	A	B	C	D	E	F
A	■		0.14			
B		■		0.03		
C	0.24		■		0.25	0.02
D			0.28	■		
E	0.28				■	
F		0.72			0.35	■

Figure 1. Quantifying the initial DSM with direct Likelihoods and direct Impacts, and calculating direct Risks

The first two quantified DSMs indicate direct Likelihoods and direct Impacts, and consequently the product is the direct Risks. Direct (or 1st order) indicates that there are no intermediate components and one component directly connects to the other. A 2nd (and higher) order of change propagation takes into consideration indirect connections as well, due to change propagating through intermediate components, therefore adding other paths of propagation.

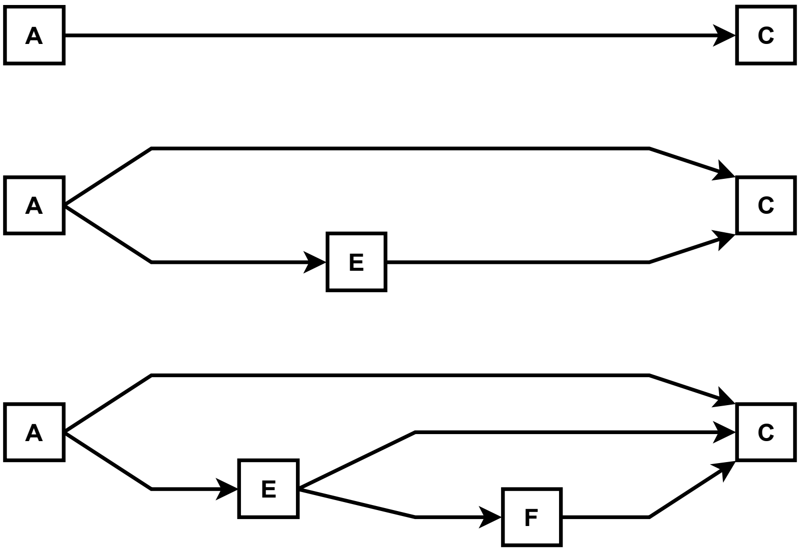


Figure 2. Different paths of change propagating from A to C, depending on order of propagation (1st, 2nd and 3rd)

To illustrate this using critical path networks, Figure 2 demonstrates the direct, 2nd order and 3rd order propagation of a change between components A and C; as defined in the DSM presented in Figure 1. It is important to notice however that the algorithm avoids cyclic routes, meaning that a component cannot be affected twice in the same path.

A number of algorithms have been developed to calculate the combined Likelihoods, Impacts and Risks, depending on the order of propagation that is of interest. The most prominent one is the forward-CPM algorithm (Clarkson, Simons and Eckert, 2004). It uses a brute-force search method and it analyses all possible paths one by one. Other algorithms for calculating the combined values have been developed and compared, for example, the trail counting algorithm (Keller, 2007) and matrix multiplication-based (Hamraz, Caldwell and Clarkson, 2013).

Suh, Weck and Chang(2007), also introduced a Change Propagation Index (CPI), that identifies whether a component is a multiplier, carrier, absorber, or constant; terms that have been defined by Keller (2007).

As mentioned in the introduction, Koh et al. (2013), include cost in their methodology but only for the receiving component. The way the cost is implemented is by multiplying the combined impact between two components with the cost of the receiving component, in order to produce the revised combined impact. This has two limitations though. First, it does not consider the cost of the intermediate components that the change is propagating through, and second, it combines the cost with another value which leads to loss of important decision-making information associated with cost.

3 PROPOSED METHODOLOGY

The proposed change prediction method, CP^2, shares some characteristics with the CPM method described in the previous section. CP^2 uses a DSM to quantify the probability of propagation (i.e. the Likelihood) but the impact measurement is removed at this stage. A new measurement, cost weight, is introduced, which is knowledge based (experts opinions), as is the case with probability of propagation. The obvious difference between impact and cost is that the former measures the design impact on the other component; the latter measures how costly a design change of the affected component will be. This means that while impact is defined at the connection between two components, using a DSM (same way as the probability), the cost is a property of each component independently. It is important to notice however that cost does not necessarily mean directly a financial one and it only represents a relative cost weight, hence the use of values between 0 and 1.

3.1 Probability of propagation

Calculation of probability of propagation between two components (considering direct and indirect change) is straightforward; simply by using probability rules for independent events. Again, as with most methods previously mentioned, independence between direct probabilities is assumed. For each critical path between components, the path probability (pp_n) is the product of all the direct probabilities (dp_{ij}) between components. In the formulation, i and j represent the components with n being the path number

$$pp_n = \prod(dp_{ij}) \qquad (1)$$

To get the combined probability Cp_{ij} of all paths from the initiating component to the receiving:

$$Cp_{ij} = 1 - \prod(1 - pp_n) \qquad (2)$$

3.2 Cost Weights & Aggregated Cost

As mentioned in the introduction, each component is assigned a cost weight. The cost weight is a value between 0 and 1 and represents how costly a design change of that component will be. For each critical path, assuming that the design change reaches the receiving component, the path cost (pc_n) is the sum of all cost weights (cw_i), including the weights of the initiating and receiving component.

$$pc_n = \sum cw_i \qquad (3)$$

To aggregate the costs of all paths between two components, each path probability is multiplied by the respective path cost and then all paths are summed. The sum of all paths is then divided by the combined probability to get the aggregate cost (Ac_{ij}):

$$Ac_{ij} = \frac{\sum(pp_n \times pc_n)}{Cp_{ij}} \tag{4}$$

As expected the aggregate cost of connection with only one path is the same as the total cost of the path since the path probability is equal to the combined probability.

We can create DSMs for combined probabilities between all components, and aggregate costs using (2) and (4). As opposed to the traditional CPM approach though, where a combined impact is calculated along with risk, an aggregated cost is not as useful on its own for decision making in the method presented here. This is due to each path having a different cost and different probability of it occurring, and combining those values leads to loss of important information. It is therefore a lot more useful to be able to see all possible path costs with their respective probability values. This will lead to a more detailed and thorough assessment of the system.

3.3 Visualization

So far a number of different approaches and methods have been used to visualize and assess the available data. DSMs can be useful in identifying connections between components and, consequently, the probability of propagation between them. To analyse connections between two specific components and visualize the corresponding propagation paths between them, a critical path analysis as the one shown in Figure 2 can be used.

When all the data have been calculated and obtained though, in order to be able to visualize all possible propagation paths between components, a multidimensional data visualization tool is mandatory. For this reason, using a DSM in this case is not possible. Therefore, parallel coordinates are employed to help visualize and analyse the paths. Parallel coordinates enables us to visualize all paths by using polylines representing the connections and the paths. The parallel axis provide the initiating and receiving components, the combined probability between components, the aggregated costs, as well as the individual path probabilities, and the path costs. Additional axis can be added to show the intermediate components in each path. This is a very powerful tool to identify patterns and for visual data mining (Inselberg, 1997)(Inselberg, 2009) and has also been used in engineering design (Kipouros et al. 2013).

The 2 quantified DSMs with combined likelihoods and aggregated costs can still be used if necessary. Further DSMs can be produced depending on the needs and data that are required to be visualized such as the worst-case scenario (highest path cost), and the most probable scenario (highest path probability).

4 CONCEPTUAL EXAMPLE

4.1 Problem Definition

To demonstrate the procedure for the proposed methodology a generic system comprising of 6 components A, B, C, D, E, and F will be considered where the components have different costs and different probabilities of propagation between them. Table 1 presents the cost weight of each component.

Table 1. Cost Weights of Components

	A	B	C	D	E	F
Cost Weight	0.6	0.7	0.2	0.1	0.5	0.9

For the direct probabilities between components, a DSM is used the same way as in CPM. Figure 3 displays the direct probabilities between components. It is worth remembering that for any given cell in the DSM, the respective column is the initiating component while the respective row is the receiving component. An example in this case would be that component A has a probability of 0.4 of directly affecting component E, but component E does not affect A, at least not directly.

	A	B	C	D	E	F
A	■		0.2			
B		■		0.1		
C	0.3		■		0.5	0.1
D			0.7	■		
E	0.4				■	
F		0.9			0.7	■

Figure 3. Direct Probability DSM

To calculate all propagation paths between components, the Cambridge Advanced Modeller (CAM) is used (Wynn et al., 2010). CAM uses the forward CPM algorithm to calculate combined Likelihoods depending on the order of propagation of interest, and identify all propagation paths between components. All DSM models and critical path networks are also produced using CAM while for the parallel coordinates the free software XDAT (X-Dimensional Data Analysis Tool) is used (XDAT, 2016).

The full calculation steps for CP^2 will be presented and explained for the propagation between 2 components (in this case A and B), and then the same procedure is applied to the whole system.

4.2 Results

In order to calculate the respective costs and probabilities between two components, each path needs to be identified and calculated individually, i.e. a brute-force search. For this example the maximum number of propagation order is considered, in this case 5th order, so that every possible path can be captured.

One useful method to visualize all the propagation paths between two components is to use critical path networks that show how change moves from the initiating component through intermediate ones, to reach the receiving component. Figure 4 shows an example of a critical path network that outlines all possible propagation paths from component A to component B. The respective direct probabilities between components and the cost weights of each one are also shown.

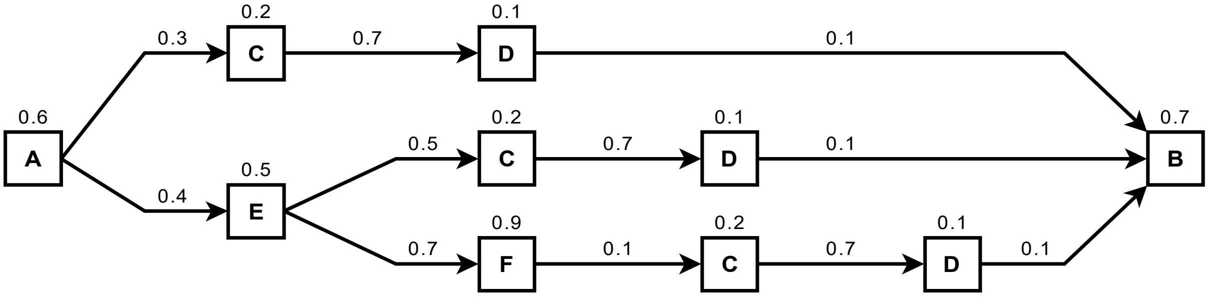


Figure 4. Different paths of change propagation from A to B. Values above components represent cost weight while values above lines represent probability

It is evident from Figure 4 that, by increasing the order of propagation, more paths are occurring. The 1st path (top one in Figure 4) would occur even with a 3rd order propagation since there only 2 intermediate components. Similarly the 2nd path would occur with a 4th order propagation but the 3rd one would require the maximum order possible since it has all the systems' components (other than the initiating and receiving ones) as intermediates.

Applying (1) for the path probabilities:

$$pp_1 = \Pi(dp_{ij}) = dp_{AC} \times dp_{CD} \times dp_{DB} = 0.3 \times 0.7 \times 0.1 = 0.021 \qquad \text{Path 1}$$

$$pp2 = 0.4 \times 0.5 \times 0.7 \times 0.1 = 0.014 \qquad \text{Path 2}$$

$$pp3 = 0.4 \times 0.7 \times 0.1 \times 0.7 \times 0.1 = 0.00196 \qquad \text{Path 3}$$

For the combined probability between A and B, which will be used to populate the combined probability DSM and calculate the aggregate costs, we apply (2):

$$Cp_{AB} = 1 - \Pi(1 - pp_n) = 1 - (1 - pp_1) \times (1 - pp_2) \times (1 - pp_3)$$
$$= 1 - (1 - 0.021) \times (1 - 0.014) \times (1 - 0.00196)$$
$$= 1 - (0.979 \times 0.986 \times 0.99804)$$
$$= 0.0366 \qquad \text{Combined Probability}$$

The cost of each path is the sum of the individual cost weights for all components:

$$pc_1 = \sum cw_n = cw_A + cw_C + cw_D + cw_B = 0.6 + 0.2 + 0.1 + 0.7 = 1.6 \qquad \text{Path 1}$$

$$pc_2 = 0.6 + 0.5 + 0.2 + 0.1 + 0.7 = 2.1 \qquad \text{Path 2}$$

$$pc_3 = 0.6 + 0.5 + 0.9 + 0.2 + 0.1 + 0.7 = 3.0 \qquad \text{Path 3}$$

To aggregate the costs for all paths between components A and B:

$$Ac_{AB} = \frac{\sum(pp_n \times pc_n)}{Cp_{ij}} = \frac{(pp_1 \times pc_1) + (pp_2 \times pc_2) + (pp_3 \times pc_3)}{Cp_{AB}}$$
$$= \frac{(0.021 \times 1.6) + (0.014 \times 2.1) + (0.00196 \times 3)}{0.0366} = \frac{0.06888}{0.0366}$$
$$= 1.8841 \qquad \text{Aggregated Cost}$$

Following the steps above, all the calculations are repeated for every combination of components and for every path between them. This will yield all values for combined probabilities, aggregated costs, path probabilities and path costs.

Even for a simple initial system as the one being considered in this example, with a small number of components and few connections, the amount of data generated can be overwhelming. This further proves the case for needing appropriate tools to visualize and assess the data.

4.3 Visualization of Results

As soon as some initial data have been obtained with regards to the propagation between components, the parallel coordinates graph can start to be constructed. Figure 5 shows a clear view of the axes that make up the parallel coordinates graph for this example along with the above calculated paths between A and B.

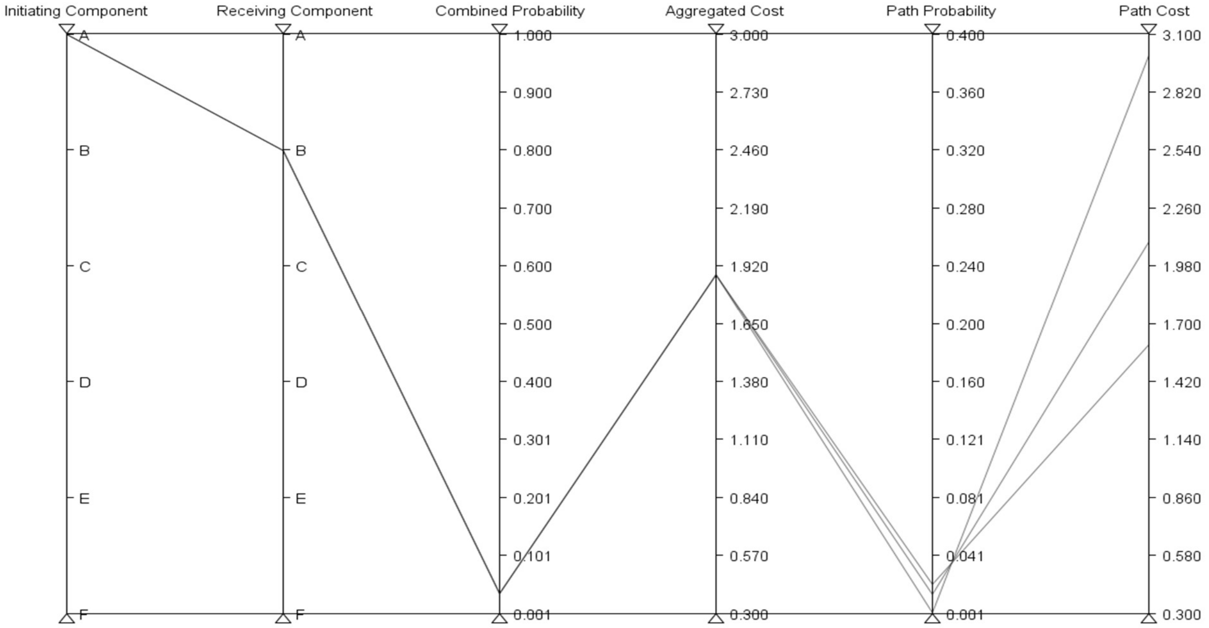


Figure 5. Parallel Coordinates outlining possible propagation paths between components A and B

Following the polyline, in Figure 5, it starts as a single line outlining the connection between the initiating and receiving component (in this case A and B), the combined probability of the connection and the aggregated cost of it. After that, the line branches out to a number of polylines, depending on the number of paths, that show the associated path probabilities and cost for each one. In this case, there are 3 paths between A and B, with each having different probability and cost. Using parallel coordinates, it immediately becomes apparent the negative relationship between path probability and path cost, i.e. the most probable path has the least cost and vice versa.

After all the data have been generated by following the aforementioned process in Section 3, two quantified DSM instances can be produced, one presenting the combined probabilities between components and the other one the aggregated costs. Figure 6 shows the 2 DSMs mentioned.

	A	**B**	**C**	**D**	**E**	**F**
A		0.018	0.2	0.0018	0.1126	0.02
B	0.0366		0.07	0.1	0.0397	0.007
C	0.4498	0.09		0.009	0.535	0.1
D	0.3307	0.063	0.7		0.3819	0.07
E	0.4	0.0072	0.08	0.0007		0.008
F	0.2973	0.9	0.1155	0.09	0.7095	

	A	**B**	**C**	**D**	**E**	**F**
A		2.4	0.8	2.5	1.4281	1.7
B	1.8841		1	0.8	1.6175	1.9
C	1.2486	1.8		1.9	0.8636	1.1
D	1.3007	1.9	0.3		0.9514	1.2
E	1.1	2.9	1.3	3		2.2
F	2.1738	1.6	2.1035	1.7	1.3966	

Figure 6. Combined Probabilities (left) and Aggregated Costs (right) for 5th order of change propagation

It becomes apparent from Figure 6 that even when considering an initial system with loosely coupled components, after a number of propagation steps, all of them become connected even with a low probability of propagation between them. While the two DSMs presented in the above figure might be beneficial for an initial view and assessment of the system as to which components can cause the highest costs, they don't capture the full picture with details since a lot of information is lost when aggregating values.

Visualizing everything using critical path networks, as shown in Figure 4, might be beneficial when examining specific components and paths, but in the case where a more detailed view of all the propagations is required, parallel coordinates are more suitable to represent all paths and their effects.

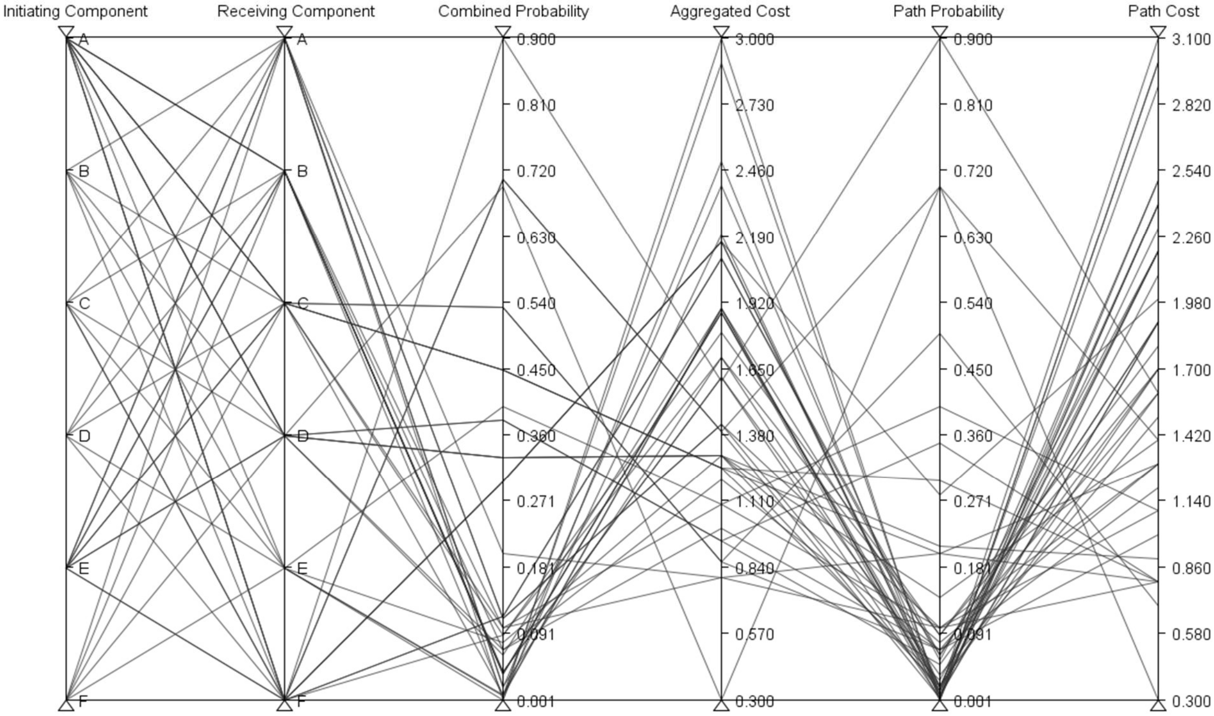


Figure 7. Parallel Coordinates outlining all possible propagation paths and associated costs for all components

Figure 7 presents the parallel coordinates visualization for the whole system being examined in this example. It captures all possible paths between components (direct or indirect), with probabilities and cost. Besides the negative relationship between path cost and path probability, a new negative relationship between aggregated cost and combined probability arises. Both observations make sense; the more intermediate components are in a path, the less probability there is of that path occurring since the probabilities are multiplied between them. At the same time the cost of the path rises as the cost of each component is added.

Parallel coordinates are very useful in visualising and interrogating multidimensional data. Static figures though of multiple polylines, such as Figure 7, might get confusing, which is the reason why most parallel coordinates tools are interactive. This allows the user to highlight specific lines or isolate lines that fall in a specific region, such as high costs or high probabilities in this case.

Additional axis can be introduced to show, not only which are the components that are affected (i.e. the intermediate ones), but any kind of measurement that can be beneficial and meaningful to the user.

5 CONCLUSION AND FUTURE DEVELOPMENTS

In this paper a novel methodology has been presented for predicting and visualizing how cost propagates in the case of engineering design changes. As part of the methodology, a novel method, CP^2, for calculating the costs associated with change propagation was developed and presented.

By utilizing existing change prediction algorithms, CP^2 introduces a cost weight for each component. This provides the ability to have a more meaningful and beneficial measurement which will assist in the decision making process when assessing and evaluating a system. The changes are propagated for all components in the system, in a similar way with the forward-CPM, and each path was then visualized with its probability and costs. Having the respective costs and probabilities of propagation for each path, the combined probabilities and aggregated costs can then be calculated for all direct and indirect connections between components.

Using various DSMs, critical path networks and parallel coordinates, all the data produced by CP^2 can be visualized in a meaningful and informative way. The detailed visualization allows a more comprehensive and detailed examination of all the possible outcomes and their respective costs in the case where a component has to go through a design change. Parallel coordinates enable the user to identify high risk areas such as paths with high costs and probabilities. By using interactive parallel coordinates, it enables the user to isolate areas and identify regions of interest to make the graph more easily understandable and interpretable.

There are a number of further improvements and modifications that will be implemented in the future. The next step is to reintroduce the impact measurement, as it is used in CPM, and integrate it in CP^2. Having the probability of propagation and impact measurement between components, along with the assigned cost weights for each one, will yield a redefined, more informative and useful, risk value. This will further utilize the capabilities of parallel coordinates.

Since the values used for probability, impact and cost are based on experts' opinions, and previous knowledge, a method for managing the uncertainty will also be introduced, i.e. by using probability distributions or fuzzy variables instead of specific crisp values. Sensitivity analysis and design of experiments of the initial state of the system is also of interest.

ACKNOWLEDGEMENTS

The work presented in this paper is part of a research project funded by the Engineering and Physical Sciences Research Council (EPSRC) and Airbus.

REFERENCES

Anderson, D.M. (1997) Agile product development for mass customization. New York: Irwin Professional Publishing.

Browning, T.R. (2001) 'Applying the design structure matrix to system decomposition and integration problems: A review and new directions', IEEE Transactions on Engineering Management, 48(3), pp. 292–306. doi: 10.1109/17.946528.

Clark, K.B. and Fujimoto, T. (1991) Product development performance: Strategy, organization, and management in the world auto industry. 2nd edn. Boston, MA: Harvard Business School Press.

Clarkson, P.J. and Eckert, C. (eds.) (2004) Design process improvement: A review of current practice. London: Springer-Verlag New York.

Clarkson, P.J., Simons, C. and Eckert, C. (2004) ‘Predicting change propagation in complex design’, Journal of Mechanical Design, 126(5), p. 788. doi: 10.1115/1.1765117.

Cohen, T., Navathe, S.B. and Fulton, R.E. (2000) ‘C-FAR, change favorable representation’, Computer-Aided Design, 32(5-6), pp. 321–338. doi: 10.1016/s0010-4485(00)00015-4.

Eppinger, S.D. and Browning, T.R. (2012) Design structure matrix methods and applications. Cambridge, MA: MIT Press.

Hamraz, B., Caldwell, N.H. and Clarkson, P.J. (2013) ‘A matrix-calculation-based algorithm for numerical change propagation analysis’, IEEE Transactions on Engineering Management, 60(1), pp. 186–198. doi: 10.1109/tem.2012.2203307.

Inselberg, A. (1997) ‘Multidimensional detective’, Proceedings of VIZ ’97: Visualization Conference, Information Visualization Symposium and Parallel Rendering Symposium, . doi: 10.1109/infvis.1997.636793.

Inselberg, A. (2009) Parallel coordinates: Visual multidimensional geometry and its applications. Dordrecht: Springer-Verlag New York.

Keller, R. (2007) Predicting change propagation : algorithms, representations, software tools. PhD thesis. Cambridge University.

Kidd, M.W. and Thompson, G. (2000) ‘Engineering design change management’, Integrated Manufacturing Systems, 11(1), pp. 74–77. doi: 10.1108/09576060010303686.

Kipouros, T., Inselberg, A., Parks, G. and Savill, A. (2013). Parallel Coordinates in Computational Engineering Design. 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. doi: 10.2514/6.2013-1750

Koh, E., Caldwell, N.H. and Clarkson, P.J. (2013). A technique to assess the changeability of complex engineering systems. Journal of Engineering Design, 24(7), pp.477-498. doi: 10.1080/09544828.2013.769207

Suh, E.S., de Weck, O.L. and Chang, D. (2007) ‘Flexible product platforms: Framework and case study’, Research in Engineering Design, 18(2), pp. 67–89. doi: 10.1007/s00163-007-0032-z.

Wynn, D.C., Wyatt, D.F., Nair, S.M.T. and Clarkson, P.J. (2010) An introduction to the Cambridge advanced Modeller. Available at: https://www.repository.cam.ac.uk/handle/1810/243227 (Accessed: 5 December 2016)

XDAT - A free parallel coordinates software tool (2016) Available at: http://www.xdat.org/ (Accessed: 6 December 2016).