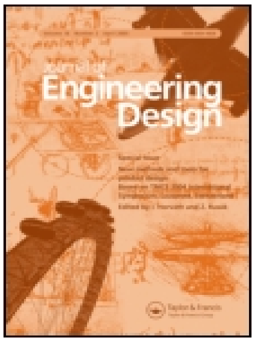

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Requirements-based development of an improved engineering change management method

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Engineering changes (ECs) are essential in complex product development, and their management is a crucial discipline for engineering industries. Numerous methods have been developed to support EC management (ECM), of which the change prediction method (CPM) is one of the most established. This article contributes a requirements-based benchmarking approach to assess and improve existing methods. The CPM is selected to be improved. First, based on a comprehensive literature survey and insights from industrial case studies, a set of 25 requirements for change management methods are developed. Second, these requirements are used as benchmarking criteria to assess the CPM in comparison to seven other promising methods. Third, the best-in-class solutions for each requirement are investigated to draw improvement suggestions for the CPM. Finally, an enhanced ECM method which implements these improvements is presented.

Keywords: engineering change management; change propagation; requirements; functional reasoning; benchmarking

1. Introduction

The British historian E. H. Carr said ‘Change is certain, progress not.’ This is certainly true of engineering changes (ECs) and highlights the role of EC management (ECM): ECs are essential and unavoidable, and the role of ECM is to make sure that the EC potential is positively utilised (Eckert, Clarkson, and Zanker 2004). EC can be broadly defined as amendments to released engineering documentation in connection with product modifications (see, e.g. Jarratt et al. 2011). ECM can be summarised according to its goals: to reduce the number of raised changes before they appear, detect them early when they occur, address them effectively, implement them efficiently, and learn continuously for the future. These guidelines were discussed by Fricke et al. (2000) under the terms: *Less*, *Earlier*, [More] *effective*, [More] *efficient*, and *Better*. ECM methods focus on executing changes *Earlier*, *More effectively*, and *More efficiently*. *Earlier* is addressed by a method if it provides means by which ECs can be detected earlier and communicated better; *More effective* is addressed by a method if it provides means by which the impact of ECs can be evaluated and used to prioritise or reject ECs; *More efficient* is addressed by a method if it allows

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*Corresponding author. Email: bh351@cam.ac.uk the implementation of necessary ECs to be completed in less time, incurring lower cost, and with better quality.

Recent literature reviews (e.g. Jarratt et al. 2011; Hamraz, Caldwell, and Clarkson 2013) reveal numerous ECM methods, amongst which the change prediction method (CPM) from Clarkson, Simons, and Eckert (2004) is one of the most established and one of the very few methods which is available as a computer tool. In this paper, we aim at improving CPM through a benchmarking approach which follows four steps. First, we develop a list of requirements for ECM methods through investigation of current methods complemented by case study experience. Second, we use these requirements as benchmark criteria to assess CPM as well as seven other promising ECM methods. The best-in-class methods for each criterion are identified. Third, we study these benchmarks and draw improvement suggestions for CPM to close the competitive gaps to the other seven methods. Fourth, we describe how an improved ECM method known as the function-behaviour-structure (FBS) linkage method was developed to address these points. The data structure of the FBS linkage method is described in detail elsewhere (Hamraz, Caldwell, and Clarkson 2012); the present paper adds an insight by detailing the modelling process and by showing how the method provides an improvement to CPM with respect to the identified requirements.

2. Review of ECM methods

In this section, an overview of current ECM methods is provided to establish the basis for the benchmarking approach that follows in the next sections.

The number of ECM methods proposed in the literature has increased rapidly in only a few years. A comprehensive list of 427 publications on ECM between the early 1980s and September 2011 was developed through a systematic literature survey (Hamraz, Caldwell, and Clarkson 2013). These publications were revisited for the present paper to generate a list of unique ECM methods. Furthermore, the review was extended to find out whether, along with the methods, a computer tool was proposed and whether this computer tool is currently available. To determine this, the publications were searched for links or hints; Google was used to search for the method name on the internet; and the departmental homepages of the first and last authors were searched. The result is shown in Table 1.

As the table shows, 54 unique methods were identified. The majority of the methods are developed across more than one publication, most notably the methods from Chen and Li and CPM. For these related publications not listed in Table 1, refer to Hamraz, Caldwell, and Clarkson (2013).

Although computer tools were proposed for 41 methods, it was determined that the tools are only actually available for four of them – the method reported by Chen and Li, CPM, CPM-House-of-Quality and House of Quality. For the other methods, a computer tool is either not explicitly reported (e.g. C-FAR), or is reported but not available. Reasons for unavailability include: the tool was implemented within a company and so is proprietary and confidential (e.g. the method from Rouibah and Caskey); the tool was not made accessible (e.g. RedesignIT); or the tool is no longer maintained (e.g. Cyber-Review).

3. Requirements-based identification of improvement opportunities for the CPM

In this section, first, a set of requirements for ECM methods is developed. Then, CPM and seven other methods are assessed against them, and subsequently, the comparison is used to draw improvement suggestions for CPM. As mentioned earlier, CPM was selected as the target for improvement because the literature review reveals it to be one of the most established methods and because the existing algorithms are implemented and accessible in an available software tool.

Table 1. ECM methods and computer tools identified through systematic literature review.

No	Method/reference name	Title or short description	Author(s) and year of respective publications	Computer tool	
				Proposed	Available
1	ADVICE	A virtual environment for ECM	Kocar and Akgunduz (2010)	x	
2	Ahmad et al.	MDM-based approach to manage EC processes across domains of the design process	Ahmad, Wynn, and Clarkson (2013)	x	
3	CECM	Integration of collaborative activities and knowledge management throughout the lifecycle of ECs	Lee et al. (2006)	x	
4	C-FAR	Change evaluation at the attribute level using matrix calculations	Cohen, Navathe, and Fulton (2000)	x	
5	Chen and Li	Pattern-based redesign planning	Chen, Macwan, and Li (2007), Li and Chen (2010)	x	x
6	Chen et al.	Methodology for ECM in the context of allied concurrent engineering	Chen, Shir, and Shen (2002)	x	
7	Cheng and Chu	Network-based assessment approach for change impacts on complex product	Cheng and Chu (2011)		
8	CIRA	Combining characteristics-properties modelling and property-driven development for change impact and risk analysis	Conrad et al. (2007)		
9	CMCEA	Change mode, cause, and effects analysis	Huang and Johnstone (1995)		
10	CPA	Change propagation analysis between items (e.g. components) considering types and levels of change	Rutka et al. (2006)	x	
11	CPD	Concurrent parameter design based on constraint network	Fan, Li, and Xiong (2004)	x	
12	CPM	CPM based on numeric component DSMs and stochastic propagation analysis	Clarkson, Simons, and Eckert (2004), Ariyo et al. (2007)	x	x
13	CPM-house-of-quality	Merging house of quality and the CPM to model the performance of different change options	Koh, Caldwell, and Clarkson (2012)	x	x
14	Cyber-review	Web-based system for ECM	Huang (2002)	x	
15	DEPNET	Re-organising design activities during EC process based on product specification dependencies	Ouertani (2008)	x	

(*Continued*)

Table 1. Continued

No	Method/reference name	Title or short description	Author(s) and year of respective publications	Computer tool	
				Proposed	Available
16	Do et al.	Propagation of EC to multiple product data views using history of product structure changes	Do, Choi, and Song (2008)	x	
17	ΔDSM	EC propagation due to requirement changes	Morkos, Shankar, and Summers (2012)		
18	EC propagator	Representation and propagation of EC information in collaborative product development using a neutral reference model	Hwang, Mun, and Han (2009)	x	
19	ECBOM	EC method based on information integration and data consistency using the bill of material	Liu and Pan (2010)	x	
20	ECD-BOM	A distributed change control workflow for design network based on a specific product configuration	Shiau and Wee (2008)	x	
21	EchoMag	Decision-making assistance in ECM process	Habhouba, Cherkaoui, and Desrochers (2011)	x	
22	Feature elasticity	Assessment of change impact on the relevant process plan	McKay et al. (2003)	x	
23	Fei et al.	Model-driven and knowledge-based method	Fei et al. (2011)	x	
24	Flanagan et al.	Change propagation through the link between functions and components	Flanagan et al. (2003)		
25	Horvath et al.	Intelligent attribute definition for integrated decision assistance	Horvath et al. (2005)	x	
26	House of quality	Mapping of customer desires to company/product capabilities	Hauser and Clausing (1988)		x
27	ITA phase II	Automatic EC analysis for incremental timing analysis	Auch and Joosep (1984)	x	
28	Joshi et al.	Systematic decision support for ECM in PLM	Joshi, Ameri, and Dutta (2005)	x	
29	Krishnamur-thy and Law	Data management model for change control in collaborative design environments	Krishnamurthy and Law (1997)	x	
30	KRITIK2	Functional model-based diagnosis in adaptive design	Goel and Stroulia (1996)	x	
31	Lee et al.	Relative change impact analysis using analytic network	Lee et al. (2010)		
32	Li et al.	ECM based on weighted complex networks	Li, Zhang, and Li (2008)		
33	Liu et al.	Change propagation graph and process model based on a Petri net to analyse change implementation	Liu et al. (2002)		
34	Ma et al.	A framework for a knowledge-supported change impact analysis system	Ma et al. (2003)	x	
35	Ma et al.	Change propagation algorithm in a unified feature modelling scheme	Ma, Chen, and Thimm (2008)	x	

36	Mehta et al.	EC impact prediction based on past changes and similarity analysis	Mehta, Patil, and Dutta (2010)		
37	Mokhtar et al.	Information model for managing design changes in a collaborative environment	Mokhtar, Bédard, and Fazio (1998)	x	
38	Ouertani	EC impact analysis in a multi technical information system context	Ouertani (2004)	x	
39	Ou-Yang and Chang	Web-based query system that enables the user to refer to the constraint information and assembly information	Ou-Yang and Chang (1999)	x	
40	PFEV model	Product Feature Evolution Validation model aiming at controlling the information flow needed to support a product definition evolution	Bouikni, Rivest, and Desrochers (2008)	x	
41	Qiu and Wong	Dynamic workflow change in PDM systems	Qiu and Wong (2007)	x	
42	Raffaeli et al.	Modelling of possible change propagation path based on components and functional flows	Raffaeli et al. (2007)	x	
43	Reddi and Moon I	Automatic identification of affected components based on change type and likeliness	Reddi and Moon (2009)	x	
44	Reddi and Moon II	A framework for ECM in enterprise resource planning using service-oriented architecture	Reddi and Moon (2011a)	x	
45	Reddi and Moon III	System dynamics modelling of ECM in a collaborative environment	Reddi and Moon (2011b)		
46	RedesignIT	Model-based reasoning to generate and evaluate proposals of redesign plans	Ollinger and Stahovich (2004)	x	
47	Roser et al.	Economic evaluation of design change options under uncertainty	Roser, Kazmer, and Rinderle (2003)		
48	Rouibah and Caskey	ECM in concurrent engineering from a parameter perspective	Rouibah and Caskey (2003)	x	
49	Tseng et al.	Evaluating a design change and the distributed manufacturing operations in a collaborative manufacturing environment	Tseng, Kao, and Huang (2008)		
50	VEC-Hub	Virtual Enterprise Collaboration Hub, an approach to enable collaborative ECM in the virtual/extended enterprise	Rosén and Almyren (2009)	x	
51	Wasmer et al.	An approach to shared, cross-organisational EC handling	Wasmer, Staub, and Vroom (2011)	x	
52	Wu et al.	Implementation and application of a CMII-based system for ECM	Wu et al. (2010)	x	
53	Xue et al.	Evolutionary design database	Xue, Yang, and Tu (2006)	x	
54	You and Chao	Propagation of design change between different CAD by using duplicate design procedures	You and Chao (2009)	x	
Total number				41	4

3.1. *Identification of requirements for ECM methods*

Systematic development of products, systems, or software starts with requirements analysis. This crucial lifecycle phase should clarify the task, create a common understanding among all stakeholders, and determine the specific needs and conditions that the developed artefact has to fulfil. The degree to which the requirements are met by the developed artefact is one measure of success.

Despite the existence of numerous ECM methods in the literature, there is not much published on requirements for ECM methods. In fact, of all the journal articles and conference papers reporting the 54 unique ECM methods in Table 1, only Lee et al. (2006) and Rouibah and Caskey (2003) appear to base their methods on an explicit analysis of requirements. Lee et al. (2006) studied the EC processes of a major Korean automobile company and determined their ECM requirements from the perspective of knowledge management and collaboration support. Rouibah and Caskey (2003) addressed requirements for multi-company ECM and grouped them into (1) Support communication, (2) Involve all relevant parties, (3) Work towards consensus, (4) Control the process, (5) Identify the scope of impact. In the research literature other authors do discuss selected requirements, but do not report a systematic analysis.

To develop a comprehensive list of requirements for ECM methods, the journal articles and conference papers describing the 54 methods were first analysed in detail. Key features of each method that the corresponding authors propose are important to its effective operation were identified, and corresponding requirements were drawn. Further requirements derived from industrial case studies and experience from our research group were added. The resulting list was studied to identify and remove duplicates. A holistic contextual framework consisting of five requirement categories was developed concurrently. The requirements were organised into these five categories and further adjusted. This process resulted in 25 requirements, listed in Table 2.

3.2. *CPM and its comparative assessment against the requirements*

CPM is a matrix-based approach that captures and quantifies component dependencies and uses them to calculate the risk of change propagation between components. It is structured into four steps (Clarkson, Simons, and Eckert 2004).

(1) The product is decomposed into its components.
(2) The direct dependencies between these components are captured in a design structure matrix (DSM). Each dependency is quantified in terms of likelihood and impact of change propagation through that dependency. The likelihood values may be estimated by considering the expected frequency of change propagation through each dependency (e.g. the proportion of all changes that propagate). The impact values indicate the effort to redesign the affected component if change does propagate, as a proportion of that required to design the component originally. Clarkson, Simons, and Eckert (2004) propose that this information may be generated by estimates from experts on the design at hand.
(3) In the third step, the Forward CPM algorithm is applied to these numeric component DSMs to compute the *combined risk of change propagation*. This algorithm applies stochastic intersection and union operators along possible change propagation paths to calculate path likelihoods and impacts while excluding self-dependencies and cyclic paths. Combined risk of change propagation is the sum of direct and indirect risk, where *direct risk* between two components is defined by the product of direct likelihood and direct impact between them, and *indirect risk* considers change spreading via intermediate components. The indirect risk from an initiator

Table 2. Requirements for an ECM method.

No	Category	Requirement name	Description of requirement capability	Selected source(s) for rationale
1	(1) Input related (scope/feasibility)	Range of products covered	Allows manageable modelling of a variety of different products, from low to high complexity	Clarkson, Simons, and Eckert (2004), Ollinger and Stahovich (2004), Chen, Macwan, and Li (2007)
2		Range of levels of decomposition supported	Allows modelling of the whole product on different levels of decomposition (i.e. system, component, part, attribute)	Cohen, Navathe, and Fulton (2000), Ariyo et al. (2007), Kocar and Akgunduz (2010)
3		Range of different changes covered	Allows modelling of changes from different kinds, i.e. domains, life cycle time, purpose, initiator, cause, target, and considers the change magnitude	Rutka et al. (2006), Ma, Chen, and Thimm (2008), Reddi and Moon (2009)
4	(2) Model building	Ease of model building	The model building procedure is easy, i.e. it can be done by any practitioner if an appropriate manual is provided	Case study experience
5		Availability of information to build the model	The required information or knowledge can be easily collected from documents (i.e. drawings, specifications, etc.) or experts (i.e. interviews etc.)	Cohen, Navathe, and Fulton (2000), Clarkson, Simons, and Eckert (2004), Kocar and Akgunduz (2010)
6		Accessibility of tools to build the model	The tools to create a model (i.e. DSM, Excel, other software programs) are available, openly accessible, or easily implementable	Case study experience
7		Accuracy	The model captures all relevant dependencies explicitly and avoids hidden and implicit dependencies between product attributes	Goel and Stroulia (1996), Ollinger and Stahovich (2004), Ahmad, Wynn, and Clarkson (2013)
8		Consistency	The model-building approach supports consistency checks, ensuring that the model is internally consistent and consistent with other models	Xue, Yang, and Tu (2006), Do, Choi, and Song (2008), Kocar and Akgunduz (2010)
9		Adaptability	A model of an existing product can be adapted to analyse a new product, i.e. existing models can be re-used easily	Goel and Stroulia (1996), Ma, Chen, and Thimm (2008), Ahmad, Wynn, and Clarkson (2013)
10		Benefit-to-cost ratio of model building	The benefit of model building (i.e. knowledge creation, communication support, etc.) outweighs the total cost of model building (i.e. material cost, personal cost)	Case study experience

(*Continued*)

Table 2. Continued

No	Category	Requirement name	Description of requirement capability	Selected source(s) for rationale
11	(3) Model use	Ease of model use	The use of the model is easy, i.e. it can be used by any designer if an appropriate manual is provided	Case study experience
12		Accessibility of tools to use the model	Support tools to use the method (i.e. DSM, Excel, other software programs) are available, openly accessible, or easily implementable	Case study experience
13		Practicality	The approach is applicable to a real situation and effective in use	Clarkson, Simons, and Eckert (2004), Ollinger and Stahovich (2004), Chen, Macwan, and Li (2007)
14		Flexibility	The model can easily be changed/updated	Chen, Macwan, and Li (2007), Kocar and Akgunduz (2010)
15		Benefit-to-cost ratio of model use	The benefit of model use (i.e. prediction capability, communication support, etc.) outweighs the total cost of model use (i.e. material cost, personal cost)	Clarkson, Simons, and Eckert (2004), Reddi and Moon (2009)
16	(4) Output related (results)	Utility of results	Provide useful analysis for different users (i.e. at different levels of detail) and depict results clearly	Rouibah and Caskey (2003), Clarkson, Simons, and Eckert (2004), Kocar and Akgunduz (2010)
17		Quantity of results	Provide sufficient and complete analyses	Rouibah and Caskey (2003), Chen, Macwan, and Li (2007), Bouikni, Rivest, and Desrochers (2008)
18		Quality of results	Provide correct and accurate results (difficult to assess!)	Case study experience
19	(5) Model related (capability/functionality)	Product modelling capability	Descriptively model the product to represent and improve product understanding and support product improvement and communication	Ollinger and Stahovich (2004), Jarratt, Eckert, and Clarkson (2004), Lee et al. (2010)
20		Change modelling capability	Descriptively model change impacts	Rouibah and Caskey (2003), Ollinger and Stahovich (2004), Ma, Chen, and Thimm (2008)
21		Change prediction capability	Predict changes caused by change propagation	Jarratt, Eckert, and Clarkson (2004), Kocar and Akgunduz (2010), Cheng and Chu (2011)
22		Change containment capability	Support causal change propagation analysis by capturing how and why changes propagate between different product attributes, to allow change control and containment	Ollinger and Stahovich (2004), Chen, Macwan, and Li (2007)
23		Solution finding capability	Enable development and testing of alternative solutions and support the solution selection process	Ollinger and Stahovich (2004), Chen, Macwan, and Li (2007), Koh, Caldwell, and Clarkson (2012)
24		Numerical analysis capability	Allow numerical and probabilistic change prediction and risk analysis	Clarkson, Simons, and Eckert (2004), Lee et al. (2010), Cheng and Chu (2011)
25		Compatibility	Support integration with other tools	Huang, Yee, and Mak (2001), Habhouba, Cherkaoui, and Desrochers (2011), Wasmer, Staub, and Vroom (2011)

to a target is defined by the sum of all risks imposed from penultimate components (other than the initiator) to the target. The imposed risk of a penultimate component to the target is the product of the combined likelihood from the initiator to the penultimate component and the direct risk from the penultimate component to the target.

(4) This combined risk matrix together with different analyses based on it are used by different stakeholders, e.g. management, product design and development, and manufacturing to support ECM decisions.

The technique has been applied to several industrial case studies with promising results; interviews with domain experts showed that the method was believed to have great potential in supporting change prediction, knowledge capture, team support, and process management (Jarratt, Eckert, and Clarkson 2004). An implementation of the method is freely available in the software program Cambridge Advanced Modeller (Wynn et al. 2010).

The 25 requirements in Table 2 were used as benchmark criteria to rate CPM alongside the most promising ECM methods. These benchmark partners were selected from the methods listed in Table 1 through a pre-assessment considering both the requirements and the availability of sufficient information for a detailed rating against the criteria. In undertaking this pre-assessment, all available publications describing each method were considered (as listed in Hamraz, Caldwell, and Clarkson (2013); Table 1 lists only the most important publications for brevity). For CPM and the method from Chen and Li, the software or the Matlab-based codes and their manuals were considered alongside research publications describing them. Eight methods were thus identified: CPM, ADVICE, C-FAR, RedesignIT, and the methods from Chen and Li, Ma et al., 'Reddi and Moon I', and Rouibah and Caskey.

For each of these methods, a detailed assessment table was prepared. To generate these assessments, the first author revisited and thoroughly reviewed each of the eight methods, rated their relative performances against each requirement using a five-point scale from 1 (poor) to 5 (excellent), and noted rationales for the ranking. To illustrate, the detailed assessment of CPM is shown in Table 3. The quality of results (Criterion 18) was excluded from this analysis, because there is insufficient published information to assess it for any of the methods. The comparative rankings and rationales were then reviewed by the co-authors and some revisions were subsequently made. Although care was taken to obtain an appropriate ranking, for instance, by comparing all methods directly to each other for one criterion at a time, it should be noted that this scoring approach involves a certain amount of unavoidable subjectivity.

The results of all eight evaluations were consolidated to highlight the best-in-class methods for each requirement (shown as the right-most column of Table 3). This analysis indicates that for 17 criteria CPM is already one of the best-in-class methods, while for the remaining seven criteria at least one other method is better. These seven criteria were viewed as 'competitive gaps' between CPM and the best-in-class methods for those aspects of change management.

3.3. *Drawing improvement suggestions for CPM*

To address the seven competitive gaps, the corresponding best-in-class methods were analysed to draw improvement suggestions for CPM. The result is summarised in Table 4.

Several ideas to implement the improvement suggestions in Table 4 were considered. Of these, the suggestions of including rationales for the links between product attributes (Criteria 7, 19, and 22) and capturing more aspects of the product in the model (Criterion 3) led to the proposal of incorporating a functional reasoning (FR) scheme into the CPM. The method that was developed from this proposal was also able to address the remaining three improvement suggestions (Criteria 2, 21, and 23), as explained in forthcoming sections.

Table 3. Rating results for CPM.

No.	Category	Requirement name	CPM score	Rationale for CPM score	Best-in-class method(s)
1	(1) Input related (scope/feasibility)	Range of products covered	5	Very broad; applied to a hairdryer, diesel engine, helicopter, etc.; relative simplicity of technique makes it applicable to product of very high complexity	CPM, Chen and Li, RedesignIT
2		Range of levels of decomposition supported	2	Only one level at a time which could be systems or components but not more detailed levels like attributes	ADVICE, C-FAR
3		Range of different changes covered	3	All kind of changes affecting components; changes to functions and behaviours must be translated to component changes; magnitude of changes not considered	Ma et al., Chen and Li, Rouibah and Caskey
4	(2) Model building	Ease of model building	5	Very easy and clear; two DSMs with direct likelihood and impact values need to be elicited	CPM
5		Availability of information to build the model	4	Good; expert interviews; basic information; limited use of available documentation	CPM, RedesignIT
6		Accessibility of tools to build the model	5	Any tools to capture two matrices (DSMs) can be used	CPM, Reddi and Moon I, Chen and Li
7		Accuracy	3	Average; expert estimations without explicit rationale	RedesignIT, Rouibah and Caskey
8		Consistency	4	High; pairwise linkage building without any sources of inconsistencies	CPM, ADVICE
9		Adaptability	4	High; existing models can be used to a certain extent and need to be manually modified to adapt to other products	CPM, C-FAR, Chen and Li
10		Benefit-to-cost ratio of model building	4	High benefit (change model; product model, communication support, etc.) and low cost (only expert interviews but no buying or programming of tools needed)	CPM
11	(3) Model use	Ease of model use	4	Easy to use; run calculation, identify changed component, read imposed change risk to other components	CPM, Reddi and Moon I, RedesignIT
12		Accessibility of tools to use the model	4	CAM tool and CPM module are freely available	CPM, Chen and Li

13		Practicality	4	High; when a component changes, the model provides information about imposed risks on other components	CPM, Chen and Li, RedesignIT
14		Flexibility	3	Average; linkage values need to be changed or defined for new components and calculations updated	All eight methods
15		Benefit-to-cost ratio of model use	4	High benefit (change prediction, communication support, etc.) and low cost (low use effort and free software)	CPM, Chen and Li, RedesignIT
16	(4) Output related (results)	Utility of results	4	High; risk profiles, critical components, depiction of change paths, etc.; clearly depicted; but no different levels of detail for different users	CPM, Chen and Li
17		Quantity of results	4	High; combined likelihood, impact, risk, for different number of steps and for the whole product; different other analyses; but currently only for one change at a time	CPM, Chen and Li
18		Quality of results	–	Not assessable	–
19	(5) Model related (capability/ functionality)	Product modelling capability	3	Average; product model shows the links between components or systems; but at high level only without hierarchical decomposition and without capturing working mechanisms	RedesignIT, Rouibah and Caskey
20		Change modelling capability	4	Good; change propagation along all possible links; but only at component level	CPM, Ma et al., Rouibah and Caskey
21		Change prediction capability	3	Average; based on estimated direct likelihood and impact values; considering all direct and indirect links; but limited accuracy and only on component level	Reddi and Moon I, Ma et al.
22		Change containment capability	2	Rather poor; no rationale of change propagation within the model; does not directly support control of propagation	Chen and Li, RedesignIT
23		Solution finding capability	2	Rather poor; only predicts change paths and shows no solutions	Chen and Li
24		Numerical analysis capability	5	Very good; numerical linkage values and algorithm for change risk calculation	CPM, C-FAR
25		Compatibility	4	Good; DSM-based results with import/export to xml and Excel files	CPM
				Other methods are better than CPM (i.e. competitive gap)	

Note: Rating scale: 1 = poor; 3 = average; 5 = excellent.

Table 4. Competitive gaps and improvement suggestions for CPM.

No	Requirement name	Selected best-in-class method(s)	Improvement suggestion for CPM	Rationale for improvement suggestion
2	Range of levels of decomposition supported	C-FAR ADVICE	Allow modelling the product and representing the results on different levels of detail at once and on more detailed levels	This will allow building CPM models on different levels of detail (i.e. the whole product on systems level and one of its systems on component level) according to the intended use and available resources, as well as facilitate use of the models by people from different departments for high level or more in-depth decisions
3	Range of different changes covered	Ma et al.	Capture product aspects other than components which might be the initial target of a change request such as functions, behaviours, structural attributes	This will allow CPM to differentiate between and thus model more types of changes
7	Accuracy	RedesignIT Rouibah and Caskey	Include rationales for the links between attributes or parameters into the model	This will improve CPM by providing a systematic basis for deciding whether a connection exists or not, thus reducing possibility of mistakes while modelling
19	Product modelling capability	RedesignIT Rouibah and Caskey	Model the working mechanisms of the product and include interfaces between domains describing different aspects of the design	This will enhance the CPM product model to create an explanatory and integrated model and improve the understanding of change implications
21	Change prediction capability	Reddi and Moon I Ma et al.	Consider links between attributes and components explicitly in the model	This will avoid the need to consider implicit links between components which lead to hidden dependencies if not captured in CPM, and thus, improve its prediction capability
22	Change containment capability	Chen and Li RedesignIT	Model change implementation alternatives and support identification of decisions that create less change propagation	This will improve CPM by allowing investigation of different change alternatives to select the best option
23	Solution finding capability	Chen and Li	Support identification of solution plans and redesign strategies	This will improve CPM by helping users to identify solutions to change requests, which is specifically helpful when it is not obvious which components to change

3.4. *Functional reasoning schemes*

In the engineering context, FR concerns theories and techniques to explain and derive functions of artefacts. FR schemes provide ways to represent and explain functions in the context of structure and/or behaviour (Far and Elamy 2005; Erden et al. 2008). A popular FR scheme is FBS, which explains how an artefact's functions are realised through certain behaviours exhibited by its structural attributes (Figure 1).

(1) *Structure* defines an artefact's composition. The structural layer of an FBS model represents the explicit parameters (McMahon 1994), which a designer directly determines in order to generate a physical solution to an abstract problem.

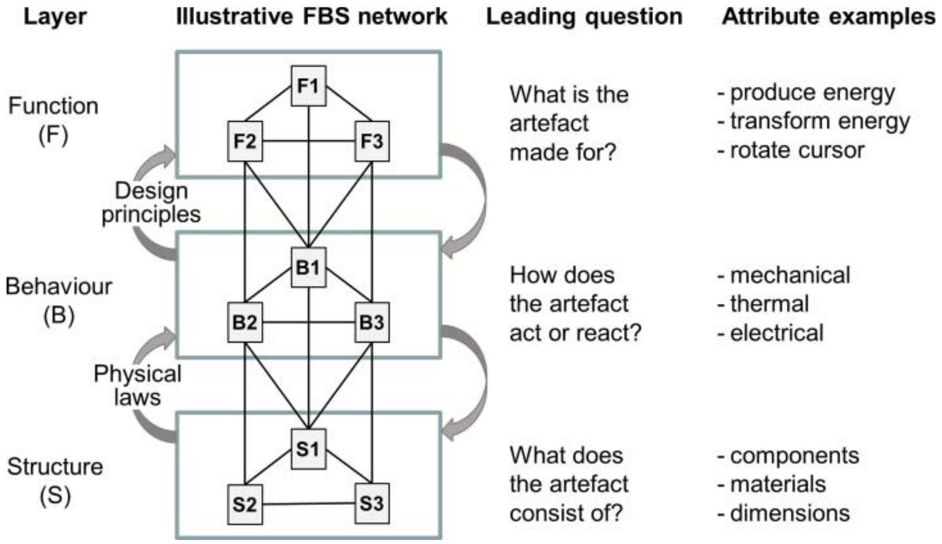


Figure 1. Schematic FBS scheme.

(2) *Behaviour* describes how an artefact responds to its environmental conditions. Behaviours may in principle be derived by applying a physical theory to the structure of the artefact and possibly some properties of the environmental conditions (Gero 1990). The behavioural layer of an FBS model represents the artefact's potential behaviours and their interrelations.

(3) *Function* describes what an artefact is intended to do. Functions are realised by selected behaviours dependent on the artefact's design (Rosenman and Gero 1998). The functional layer of an FBS model represents the artefact's sub-functions and their interrelations.

A design modelled using an FBS scheme can be represented as a multi-layered network composed of functional, behavioural, and structural attributes. Attributes within a layer and in any two adjacent layers may be interlinked, as depicted in Figure 1. All three layers may in principle include hierarchical structures decomposing high-level attributes into more finely grained attributes (Umeda et al. 1990; Goel and Bhatta 2004).

4. Implementing the improvement suggestions

4.1. *Overview of the FBS linkage method*

The FBS Linkage method enhances CPM by replacing its component-based product linkage model with an attribute-based FBS scheme. The original CPM approach treats the dependencies between components as black boxes and stipulates that the likelihood and impact values should be based on expert estimations, without capturing rationales. The incorporation of an FBS scheme clarifies those dependencies by decomposing them into causal attribute relations. This allows users of the FBS Linkage method to model changes at the more detailed level of attributes, while also improving their understanding of why and how changes propagate in the first place and thus enabling proactive change management, as detailed in Section 4.3. Any element of the FBS network can be used to represent the initial target of a change request, and the network shows how a change to one element might propagate along the links to other elements.

The FBS scheme used in the method adapts Gero's FBS model (see, e.g. Rosenman and Gero 1998) for the behavioural and structural layers, and combines it with the reconciled functional basis reported by Hirtz et al. (2002) for the functional layer. The latter was included because it supports the development of systematic and unambiguous functional block diagrams by providing a comprehensive dictionary of functions and flows. This ontology helps reconcile different notions of function, which otherwise can lead to inconsistencies while modelling the function structure of an existing design (Eckert et al. 2011).

An earlier version of the FBS Linkage method including details on the ontology and underlying assumptions is reported in (Hamraz, Caldwell, and Clarkson 2012). That information will not be repeated here, but is complemented with additional material – specifically (1) a stepwise technique explaining how to build and use an FBS Linkage model, and (2) a comparison and thus evaluation of the FBS Linkage method against other ECM methods using the benchmarking approach.

4.2. *Steps in the FBS linkage method*

The FBS Linkage method proceeds in four steps as depicted in Figure 2. These steps are explained in the following subsections.

4.2.1. *Develop FBS scheme*

The FBS Linkage method starts with development of an FBS scheme for the design to be analysed. Depending on the desired level of detail, a design can be decomposed into its systems, assemblies, components, parts, or a mix of those, if, for instance, some systems need to be modelled in greater depth than others. The structural and behavioural attributes of each such constituent must then be determined and linked together. For the structural layer, a number of ideally independent attributes such as material, geometry, surface, colour, and control hardware (i.e. transistors, chips, microprocessors) can be considered. For the behavioural layer, different types of preferably independent behaviours such as mechanical, thermal, and electrical should be identified. If those structural or behavioural attributes are not independent, their relations should also be captured. This requires more effort and leads to a more complex network than would otherwise be the case.

In general, there is an appropriate number of independent types of structural or behavioural attributes. With reference to Hubka and Eder's *elementary design properties (i.e. form, dimensions, materials, surface)* and *general design properties (i.e. strength, stiffness, corrosion, pollution, hardness, noise emissions, etc.)* (Hubka and Eder 1996, 112) and McMahon's *explicit attributes* '[which] must be must be explicitly defined for the artefact to be made' and *implicit attributes* 'which describe the characteristics and behaviour of the artefact subjected to the external effects' (McMahon 1994, 198), it is reasonable to assume that a fixed set of structural and behavioural attribute types may be determined for inclusion in a model, although the number of types may vary from case to case. If fewer attribute types than this are defined, the attributes are more likely to be insufficiently distinct and thus dependent; if more attribute types than this are defined, the attributes are more likely to be part of a higher level attribute and thus dependent. For instance, if only the two structural attribute types *Dimensions* and *Contents* were defined, it may not be clear to which of these two groups attributes such as form, shape, and surface belong and this could

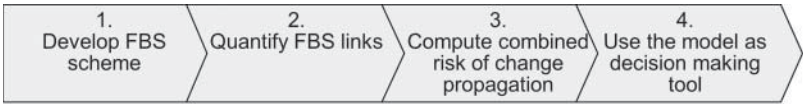


Figure 2. The FBS linkage method.

lead to dependencies between Dimensions and Contents. On the other hand, if the Dimensions attribute was divided into *Axial dimensions* (length, width, height) and *Radial dimensions*, the radius of a cylinder could determine its width and this could lead again to dependencies between them.

The functional layer considers the whole product and has a separate hierarchical structure, independently from the level of decomposition of the product into systems, components, or parts. This layer comprises a functional block diagram composed of functions interlinked by flows of energy, material, and signal according to the reconciled functional basis from Hirtz et al. (2002).

Finally, the three layers are connected to each other to complete the FBS scheme. The structural attributes that determine component behaviours are linked to each other, and to the behavioural elements that realise the functions. Because the relation between structure and behaviour is determined by physical laws that apply to all components, the mapping between structural and behavioural attributes can be developed independently from the components. However, for some components certain links might be irrelevant for EC propagation and can be omitted, e.g. the influence of the structural attribute colour on thermal behaviour is often insignificant in comparison to the influence of material on thermal behaviour.

4.2.2. *Quantify FBS links*

Similarly to CPM, the FBS links need to be quantified by likelihood and impact of change propagation. While the original CPM approach only captures the links between components, and subsumes all types of interactions (i.e. structural, behavioural, and functional) into a single number, the FBS links are more detailed and specific. The existence of a link between any two elements may be explained based on reasoning in the context of the product's functions and working mechanisms.

In principle, at least some of the impact and likelihood values might be possible to calculate directly. For instance, the dependency between *Material* and *Thermal behaviour* might be described using mathematical equations which relate their parameters to each other. Where such calculations are possible and feasible with a reasonable amount of effort, objective values can replace the estimations, and this will improve the model's fidelity. An algorithm to achieve this under some circumstances is discussed in (Hamraz et al. 2013). However, maintaining the probabilistic character of CPM is generally appropriate. The probabilistic approach reduces the complexity and effort of model building, because estimated linkage values are much easier to obtain than the results of deterministic calculations.

4.2.3. *Compute combined risk of change propagation*

The Forward CPM algorithm is applied to the numerical FBS matrices to calculate a combined risk matrix. Because the FBS network consists of three layers that are connected in series, at least four steps of change propagation are required to consider indirect change propagation between two structural or functional elements across all other layers (e.g. S1 → B1 → F1 → B2 → S2). This is two steps more than in the single-layered CPM network. Therefore, we suggest five or six steps of change propagation for the FBS Linkage model, two steps more than Clarkson, Simons, and Eckert (2004) use for CPM.

4.2.4. *Use the model as decision-making tool*

Finally, the combined risk matrix along with the FBS scheme itself can be used to support ECM decisions. The FBS risk matrix is more detailed than the CPM risk matrix, in that it includes calculated risk values not only between components but between their structural and behavioural attributes and the product's functions. To inform high-level judgements, these values can be aggregated (e.g. into risks for propagation between components, subsystems, etc.) or collapsed to represent different views on how change can propagate (e.g. between attributes, across layers, etc.). Different operations (e.g. maximum, average, etc.) can be used to obtain these aggregated values from the individual values dependent on the risk affinity of the user, which may be influenced by guidelines for risk estimation issued by the company.

For instance, if the user or company has a neutral risk appetite and thus expects that the extreme values at the lower and upper end of the risk scale balance each other out, the aggregated values may be calculated by building unweighted averages of the single values. If the user or company has an optimistic risk appetite, they may choose an aggregation function that neglects extreme values at the higher end of the risk scale. If they are very risk averse, the maximum operation is appropriate, i.e. the aggregated risk values are determined by the maximum of the corresponding single risk values. This generates a matrix of 'worst case' propagation risks. The choice of aggregation function influences the visualised risk of change propagation, and thus may affect whether a change assessed using the method appears feasible to implement given the user's appetite for risk.

Similarly to CPM, the risk values can be used to assess change cost, prioritise components or elements according to their imposed risk, and characterise them according to their change absorption degree.

In addition to this quantitative change prediction analysis, the FBS Linkage model can be applied to reason about changes for the purpose of solution development and change containment. For instance, when a function has to be changed, tracing links in the FBS network allows identification of the different behaviours which realise this function and, in turn, the structural elements which exhibit those behaviours. Studying the network thus helps to identify the elements that could be involved in a change. At the same time, it can be used to investigate which elements should be manipulated to accommodate the functional change most effectively.

4.3. *An illustrative example*

In this subsection the FBS Linkage method is demonstrated using a hairdryer as an illustrative example.

4.3.1. *Develop FBS scheme for the hairdryer*

First, the hairdryer was decomposed into six components. Next, the three layers of the product and their interrelations were modelled and visualised using both network and matrix representations.

On the component level, the structural layer is composed of components, their structural attributes, and structural interrelations. For each of the six hairdryer components, five structural attributes were defined – Geometry, Material, Colour, Surface, and Control hardware – leading to $5 \times 6 = 30$ structural elements (Figure 3). The structural links can be captured independently using separate DSMs for each structural attribute, where 'x' indicates the existence of a link (Figure 4(a)) and then summarised into a block matrix (Figure 4(b)).

Assuming that the structural attributes are independent from each other on the structural level, the off-diagonal blocks in Figure 4(b) remain empty. This implies that, in case there were no functional and behavioural dependencies, those attributes could be independently determined and any combination would be possible. For instance, while the geometry of interlocking parts must be interdependent, and the materials of those parts may be interdependent, any suitable set of materials could be combined with any suitable set of geometries. However, when behaviours and

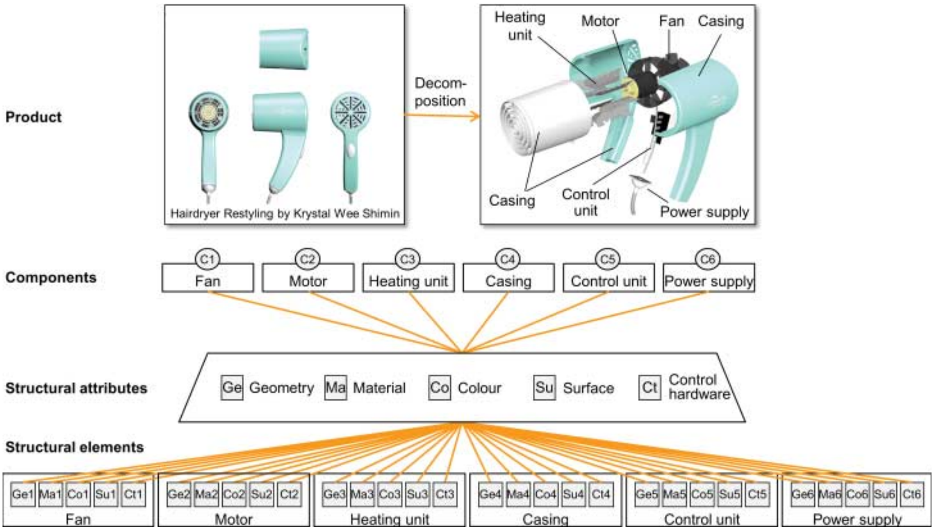
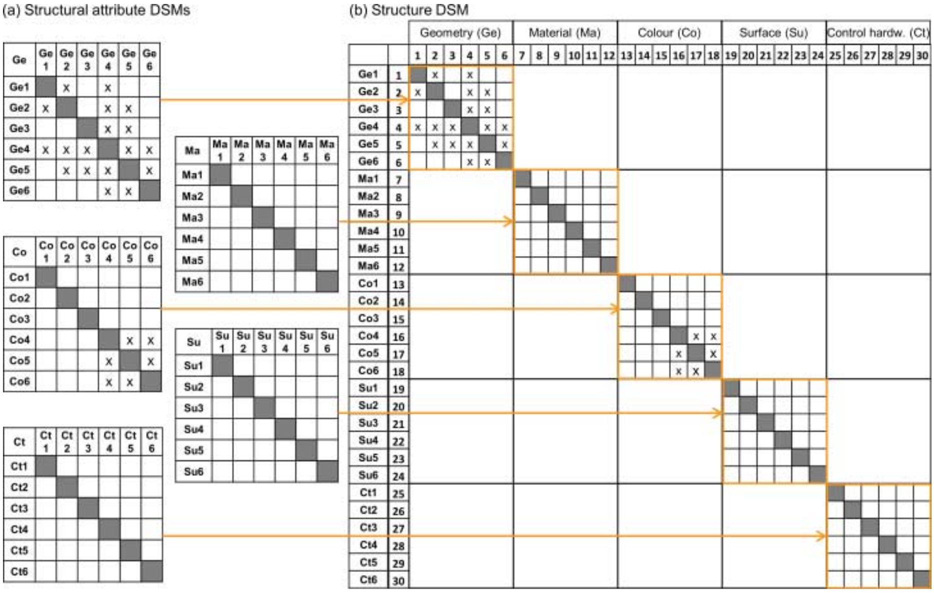


Figure 3. Structural attributes and structural elements of the hairdryer.



Ge	Ge 1	Ge 2	Ge 3	Ge 4	Ge 5	Ge 6
Ge1	■	X		X		
Ge2	X	■		X	X	
Ge3			■	X	X	
Ge4	X	X	X	■	X	X
Ge5		X	X	X	■	X
Ge6				X	X	■

Ma	Ma 1	Ma 2	Ma 3	Ma 4	Ma 5	Ma 6
Ma1	■					
Ma2		■				
Ma3			■			
Ma4				■		
Ma5					■	
Ma6						■

Co	Co 1	Co 2	Co 3	Co 4	Co 5	Co 6
Co1	■					
Co2		■				
Co3			■			
Co4				■	X	X
Co5				X	■	X
Co6				X	X	■

Su	Su 1	Su 2	Su 3	Su 4	Su 5	Su 6
Su1	■					
Su2		■				
Su3			■			
Su4				■		
Su5					■	
Su6						■

Ct	Ct 1	Ct 2	Ct 3	Ct 4	Ct 5	Ct 6
Ct1	■					
Ct2		■				
Ct3			■			
Ct4				■		
Ct5					■	
Ct6						■

Figure 4. (a) Structural attribute DSMs and (b) structure DSM of the hairdryer.

functions are taken into account, it is clear that structural attributes cannot usually be determined independently. For instance, the weight of a component is determined by both material and geometry, so these two structural attributes must be considered in combination during the design process and should be linked indirectly in the FBS scheme.

If structural attributes are not independent on the structural level, for instance, if the material of a component influences important properties of its surface, their interrelations could be captured in the corresponding off-diagonal blocks in Figure 4(b). This increases the number of dependencies in the model and correspondingly increases the change propagation risk calculated using the Forward

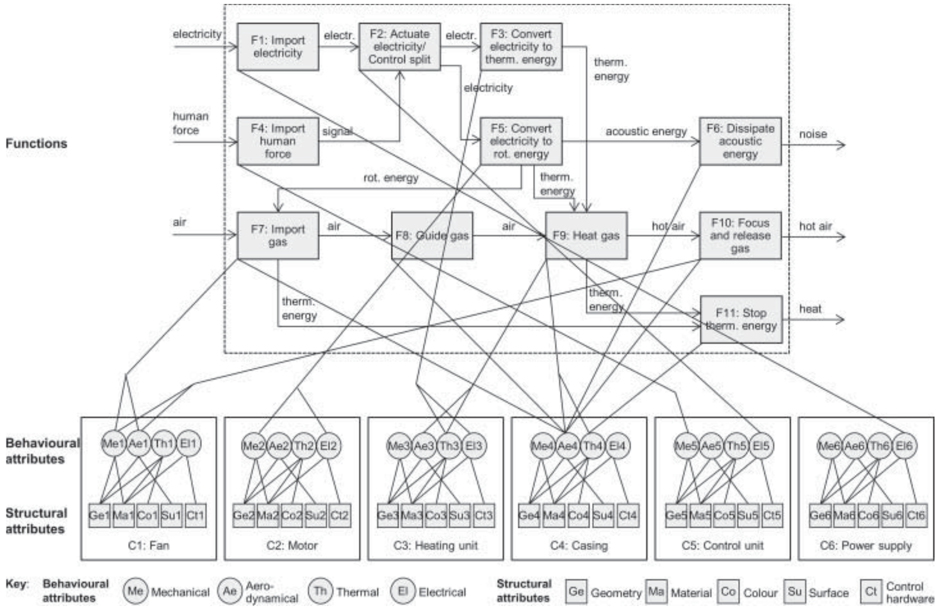


Figure 5. FBS scheme of the hairdryer. Note: Intra-layer links are depicted only for functions.

CPM algorithm. Thus, dependent on the definition of the structural attributes, the resulting risk profile might change.

For the hairdryer, links between its components within the geometry and colour attributes were identified. The material, surface, and control hardware elements are structurally not linked to each other. This is shown in Figure 4.

The behavioural layer can be modelled following a similar procedure. This layer is composed of component behavioural attributes and their behavioural interrelations. For each of the six hairdryer components, four relevant behavioural attributes were defined – Mechanical, Aerodynamic, Thermal, and Electrical behaviours – leading to $4 \times 6 = 24$ behavioural elements. For simplicity, these behaviours were assumed to be independent in the hairdryer model. Especially for the Thermal and Electrical behaviours, which are usually interdependent, this simplification could be refined by adding links to the matrix fields between the Thermal and Electrical matrix blocks to consider their relations. Using the functional basis from Hirtz et al. (2002), for the hairdryer, 11 sub-functions were identified and linked together by flows of signal, electricity, air, thermal energy, rotational energy, and acoustic energy in a function network (Figure 5). Although the functional links in this network are represented as directed to indicate the flows, for change propagation and thus within the FBS Linkage model they were considered to be undirected. In consequence, changes can propagate in both directions irrespective of the flow orientations. This is reasonable, because a change to a given function might affect both its input and output. For instance, a change to ‘Convert electricity to rotational energy’ (F5) which aims at increasing the rotational energy might impact not only its successor function ‘Import gas’ (F7) – because the higher rotational energy might increase the volume of imported gas – but also its predecessor function ‘Actuate electricity/Control split’ (F2) – because more electrical energy would likely be required.

Finally, using a network diagram, the structural elements were linked to the behavioural elements that they determine and the latter to the functions that they realise. The resulting FBS network for the hairdryer is represented in Figure 5, where the intra-layer links for the structural and behavioural layers are omitted to preserve graphical clarity. This network shows how the FBS Linkage method improves upon CPM from the point of view of requirement 19 (Product modelling capability), because it models the working mechanisms of the hairdryer in significantly greater detail.

Although this model appears complex, the network was constructed through a straightforward logical process once the functional block diagram and components had been identified. The line of reasoning can be illustrated considering, for instance, the ‘Focus and release gas’ function (F10). This was mapped to its implementing components, Fan (C1) and Casing (C4). Each component was then considered to determine the behavioural attributes involved in the function under consideration. In the case of the Fan, for example, its Mechanical (Me1) and Aerodynamic (Ae1) behaviour are involved in the ‘Focus and release gas’ function (F10), while its Thermal (Th1) and Electrical (El1) behaviours are not. Finally, the behaviours thus identified were considered to identify which of the structural attributes are relevant to them. For example, Mechanical (Me) behaviours are affected by the Geometry (Ge) and Material (Ma) attributes of a component only. The connections between structural and behavioural attributes can as a first approximation be the same for each component, as shown in Figure 5, because these interdependencies are created by physical laws common to all components. This means that model-building effort is far lower than it may initially appear. As can be seen from this example, the mappings can be built up fairly unambiguously by considering functions and their physical embodiment one-at-a-time. This shows how the FBS Linkage method improves upon CPM from the point of view of the requirement 7 (Accuracy), because it requires making the nature of the links explicit during model-building.

4.3.2. *Quantify FBS links for the hairdryer*

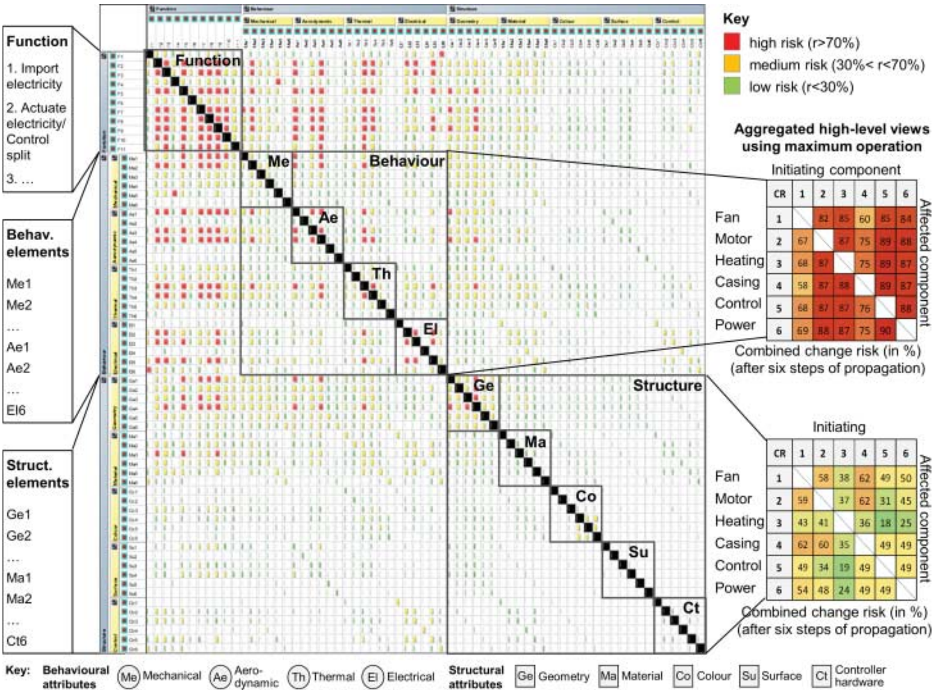
The links in the FBS scheme were quantified in terms of likelihood and impact of change propagation using three different values, 0.3 for low, 0.5 for medium, and 0.8 for high. To estimate these values, the relations between directly linked attributes were investigated for generic changes. For instance, if the diameter of the Fan (C1) is increased, it will require the Casing (C4) diameter to be increased accordingly to house the bigger Fan whereas a decrease of the same diameter will not propagate to the Casing. Assuming that 50% of the generic change cases require an increase and 50% a decrease of the Fan size, it can be concluded that the likelihood of change propagation from the Geometry attribute of the Fan (Ge1) to the Geometry attribute of the Casing (Ge4) is 0.5. The impact of change propagation for this link is low (0.3) as in case of actual propagation, not the whole Casing has to be re-designed but only the corresponding diameter. Similarly, all other intra-layer links were quantified individually. The inter-layer links between structural and behavioural attributes were set to have equal likelihood and impact for all components and changed for exceptional components afterwards.

4.3.3. *Compute combined risk of change propagation for the hairdryer*

Subsequently, the Forward CPM algorithm was applied to calculate the combined risk values, considering six steps of change propagation. As a result, the combined risk multi domain matrix (MDM) represented in Figure 6 was generated.

4.3.4. *Use the model as a decision-making tool*

This MDM can be collapsed or aggregated in different ways to generate specific high level views of change propagation. For example, as depicted in the right hand side of Figure 6, the structural or behavioural attributes can be aggregated to produce a component-component DSM which includes the combined linkage values for all structural or behavioural attributes. While the MDM incorporates the detailed FBS information useful for tracing specific change paths, these collapsed



	CR	1	2	3	4	5	6
Fan	1		82	85	60	85	84
Motor	2	67		87	75	89	88
Heating	3	68	87		75	89	87
Casing	4	58	87	88		89	87
Control	5	68	87	87	76		88
Power	6	69	88	87	75	90	

	CR	1	2	3	4	5	6
Fan	1		58	38	62	49	50
Motor	2	59		37	62	31	45
Heating	3	43	41		36	18	25
Casing	4	62	60	35		49	49
Control	5	49	34	19	49		49
Power	6	54	48	24	49	49	

Figure 6. Resulting combined risk MDM and aggregated high-level views for the hairdryer (attribute-clustered).

views provide a high-level overview. For instance, the component-component DSM indicates the overall propensity of each component to receive or transmit change. This example indicates how the FBS Linkage method can be used to produce results on different levels of detail, and thus, improves upon CPM from the point of view of requirement 2 (Range of levels of decomposition supported). Finally, the FBS Linkage model and the resulting combined risk MDM were used to evaluate different change cases, and were found to be insightful and helpful. Some example applications that show how the model can support decision-making are presented in the next subsections.

4.4. *Example use case*

Consider the situation in which a designer has to increase the heating power of a hairdryer design from 1200 to 1400 W. This change request is not directly targeted to any specific component but to the functional layer of the hairdryer. Using the FBS Linkage network, the initial change target can be located as the ‘thermal energy’ flow between the ‘Convert electricity to thermal energy’ (F3) and ‘Heat gas’ (F9) functions. This flow has to be increased to provide 1400 W heating power. This indicates how the FBS Linkage method improves upon CPM from the point of view of requirement 3 (Range of different changes covered), because it allows evaluation of changes that are initiated in any product attribute or link.

Actual implementation of changes requires manipulation of explicit parameters in the design (i.e. structural attributes). Changes that target the product’s functions have to be traced back to the responsible behaviours and those behaviours, in turn, to the structural attributes that trigger them. To determine how the change above might be implemented, the designer can trace the linkages in the FBS Linkage model to determine the structural attributes that must be manipulated. In this case the functional flow connection suggests that F3 or its input flow might require a change.

More specifically, it can be deduced that the electricity input of F3 should be increased to produce more thermal energy. To accommodate this change to F3, the Electrical (El3) and Thermal (Th3) behaviours of the Heating unit (C3) which realise F3 may require changes accordingly, if they cannot support the higher electricity input. These behaviours, in turn, are determined by the structural attributes of the Heating unit which can be identified by following a similar procedure.

This example shows how a concrete change plan can be developed for an abstract change request and highlights the FBS Linkage method's improvement upon basic CPM from the point of view of the requirement 23 (Solution finding capability). The reasoning-based and explanatory FBS model supports the designer in finding the implementation levers and developing solutions to change requests.

Most change requests can be implemented through different alternatives. For instance, if Th3 needs to be changed to support the higher conversion of electricity into thermal energy, it might be implemented by modifying the Heating unit's Geometry (Ge3), improving its Material (Ma3), or changing its Colour (Co3). To determine which option is preferable, the designer may investigate the links between those structural attributes and other attributes. The FBS Linkage model shows that Ge3 is interconnected to Ge4 and Ge5, while Ma3 and Co3 are not (Figure 4). Alternatively, the combined risk MDM from Figure 6 might be used to compare the imposed risk profiles of these attributes. This suggests that the imposed change risk of Ge3 is higher than Ma3 or Co3. Therefore, if the cost of these alternatives is equal, it is better to accommodate the change by using a better Material or a different Colour.

This example demonstrates how the FBS Linkage method improves upon basic CPM from the point of view of the requirement 22 (Change containment capability) because it shows the different alternatives for the implementation of a given change and supports the selection of the best alternative.

Furthermore, tracing the links in the network suggests that some other functions such as 'Heat gas' (F9), 'Actuate electricity/control split' (F2), and 'Import electricity' (F1), and their inputs might require changes. Those functions are realised by the behavioural attributes of the Heating unit (C3), Casing (C4), Control unit (C5) and Power supply (C6) which would then be investigated accordingly. The systematic basis and comprehensive product model of the FBS Linkage method ensure that the implications of a change on other functions and components are not overlooked, indicating how the FBS Linkage method improves upon CPM from the point of view of requirement 21 (Change prediction capability).

This hypothetical case might appear to imply that the chain of affected attributes is endless, but in practice the propagation chain will come to a halt after a few steps because some attributes will be able to tolerate changes and some others are frozen. The former absorb changes and stop the propagation chain. Frozen attributes cannot be changed; when these nodes are identified while tracing changes through the FBS linkage network, the change must be stopped at that point or redirected, so that it is implemented by changing some other attributes. Further discussion on design freeze and its effect on change propagation paths can be found in Eger, Eckert, and Clarkson (2005).

5. Summary and evaluation of FBS linkage against the requirements

The literature survey, the development of the requirements, and the execution of the proposed benchmarking approach produced results that contribute to the state of the art of ECM. To outline:

- Drawing on the literature review and categorisation, 54 unique ECM methods were identified and classified according to their availability in computer tools. Table 1 thus provides an overview and brief description of current ECM methods with the main references for each.

- A comprehensive set of 25 requirements for ECM methods was developed (Table 3). These requirements were obtained from the publications on the 54 unique ECM methods identified within the categorisation framework, combined with industrial experience from several case studies. The requirements set can provide guidance for improvement of current ECM methods and development of future methods.
- A competitive assessment of the eight most promising ECM methods was conducted using the set of requirements as benchmark criteria. These eight methods were selected from the list of 54 unique ECM methods, thoroughly reviewed and rated against the requirements. For each requirement, the best-in-class methods were identified. This list could be used to select the method that best meets a particular set of needs. However, it should be appreciated that the generation of the list involved some unavoidable subjectivity.
- For CPM, a detailed assessment table including the scores and rationales was prepared and contrasted against the best-in-class methods. This analysis identified the competitive gaps for CPM. For these criteria, the best-in-class methods were investigated and improvement suggestions

Table 5. Summary of FBS Linkage method improvements to CPM.

No	Requirement name	Improvement suggestion for CPM		Implementation in FBS Linkage method	Paper section
2	Range of levels of decomposition supported	Allow modelling the product and representing the results on different levels of detail at once and on more detailed levels	◀	FBS Linkage method is based on a detailed model including different types of design attributes. This allows results to be aggregated to different levels of detail	4.3.4
3	Range of different changes covered	Capture other product aspects which might be the initial target of a change request, such as functions, behaviours, structural attributes	◀	FBS Linkage method explicitly considers functional, behavioural, and structural attributes of the product and allows evaluation of changes that are initiated in any product attribute or link	4.4
7	Accuracy	Include rationales for the links between attributes or parameters into the model	◀	FBS links can be explained in the context of the product functions and working mechanisms. The method makes the nature of the links explicit during model-building, which helps avoid overlooking propagation paths	4.3.1
19	Product modelling capability	Model the working mechanisms of the product and include interfaces between domains describing different aspects of the design	◀	FBS Linkage scheme explains how the product realises its functions; thus it models the working mechanisms of the hairdryer in significantly greater detail than CPM	4.3.1
21	Change prediction capability	Consider links between attributes and components explicitly in the model	◀	The systematic basis and comprehensive product model of the FBS Linkage method ensure that the implications of a change on other functions and components are not overlooked	4.4
22	Change containment capability	Model change implementation alternatives and support identification of decisions that create less change propagation	◀	Tracing the FBS linkage model suggests different alternatives for implementation of a given change and supports selection of the best alternative	4.4
23	Solution finding capability	Support identification of solution plans and redesign strategies	◀	The FBS model captures reasoning behind the design and thus supports finding implementation options and developing solutions to change requests	4.4

Table 6. Rating of FBS Linkage method against the 25 requirements and CPM.

No	Category	Requirement name	CPM score	FBS linkage score	FBS linkage rationale
1	(1) Input related (scope/feasibility)	Range of products covered	5	5	Very broad; applied on hairdryer, diesel engine, scanning electron microscope; supported hierarchical decomposition allows managing of modelling effort and complexity, i.e. products of higher complexity can be modelled on a higher level of decomposition to reduce effort
2		Range of levels of decomposition supported	2	4	Models systems, components, and attributes
3		Range of different changes covered	3	4	All kind of possible changes to functions, behaviours, attributes, and their relations; magnitude of changes not considered in numerical change prediction analysis but could be taken into account in qualitative case-by-case analysis
4	(2) Model building	Ease of model building	5	3	Average; model building process well described; developing of the functional block diagram requires expert knowledge
5		Availability of information to build the model	4	3	Average; expert interviews; basic information; available documentation about the product's architecture, functions, and working mechanism
6		Accessibility of tools to build the model	5	5	Any tools to capture DSMs can be used
7		Accuracy	3	4	High; expert estimations with causality as rationale
8		Consistency	4	4	High; consistency ensured in the context of the product's functions and causality; model elements and links well defined
9		Adaptability	4	4	High; existing models can be used to a certain extent and need to be manually modified to adapt to other products
10		Benefit-to-cost ratio of model building	4	4	Very high benefit (detailed causal product model can be used for change modelling, FR, communication support, etc.) and medium cost (much information but no programming or buying of tools needed)
11	(3) Model use	Ease of model use	4	3	Average; easy numerical prediction analysis: run calculation, identify changed element, read imposed change risk to other elements; rather complicated use for qualitative case-by-case change propagation analysis as expert knowledge required to determine propagation paths and develop solutions
12		Accessibility of tools to use the model	4	3	Java-based CAM tool and CPM module (both available for free) can be used in combination with Microsoft Excel. An FBS Linkage module in CAM is in development

(*Continued*)

Table 6. Continued

No	Category	Requirement name	CPM score	FBS linkage score	FBS linkage rationale
13		Practicality	4	4	High; when a component attribute or function changes, the model provides information about imposed risks on other component attributes or functions; moreover, the model can be used for FR purposes
14		Flexibility	3	3	Average; links and linkage values need to be changed or defined for new component attributes and functions and calculations updated
15		Benefit-to-cost ratio of model use	4	4	Very high benefit (numerical change prediction, causal change propagation, FR, communication support, etc.) and medium cost (fairly low use effort and free software)
16	(4) Output related (results)	Utility of results	4	4	High; risk profiles, critical components, depiction of change paths, etc.; clearly depicted; but no different levels of detail for different users
17		Quantity of results	4	4	High; combined likelihood, impact, risk, for different number of steps and for the whole product; different other analyses; but currently only for one change at a time
18		Quality of results	–	–	
19	(5) Model related (capability/ functionality)	Product modelling capability	3	4	Good; causal product model including component breakdown, structural, and behavioural attributes, and functions
20		Change modelling capability	4	4	Good; change propagation along all possible attribute and function links
21		Change prediction capability	3	4	Good; change prediction considering all direct and indirect links between attributes, components, and functions
22		Change containment capability	2	4	Good; causal relations in the FBS Linkage network can help to contain changes
23		Solution finding capability	2	4	Good; the FBS Linkage scheme could be used to find solutions for changes, thereby considering functions, behaviours, and structures
24		Numerical analysis capability	5	5	Very good; numerical linkage values and algorithm for change risk calculation
25		Compatibility	4	4	Good; DSM-based data with import/export to xml and excel files

Other methods are better than CPM (i.e. competitive gap)	Improvement on CPM	Degradation on of CPM

Note: Rating scale: 1 = poor; 3 = average; 5 = excellent.

for CPM were drawn. This qualitative evaluation of the competitive shortcomings and potential improvement opportunities of CPM could provide insight to further improve CPM. Furthermore, using the same approach a detailed profile could be developed for any other ECM method, and used to identify competitive gaps as starting points for improvement.

Based on the improvement suggestions drawn for CPM, a concept for an improved ECM method was developed and implemented in an enhanced ECM method termed FBS Linkage. This method implements the suggested improvements to CPM as summarised in Table 5.

Although the method improves on CPM in these respects, it also introduces some weaknesses. Most importantly, basing the method on an FR scheme instead of simple component dependencies increases the effort and complexity of model building and use (i.e. ease and availability of information and tools to build and use the model). However, the effort increase is not in proportion to the increased size of the matrix, because the majority of the FBS MDM fields are empty and can be skipped when modelling (as can be seen from Figure 4). The total effort to build the model for the hairdryer was in the order of 10 man-hours. The method has also been successfully applied to a diesel engine (Hamraz, Caldwell, and Clarkson 2012). For the diesel engine with 42 components and 40 sub-functions, the total effort was in the order of 60 man-hours. Further ongoing applications include a scanning electron microscope.

Having modelled different products, it is clear that existing FBS Linkage models can vastly facilitate building new ones, thus further reducing the modelling effort. The main benefit comes from the structural and behavioural layers and their interrelations, which are similar for different products. The functional layer is unique to each product, but shows high similarities between variants of the same family. From the case studies we have conducted so far, we believe that the benefits of the method outweigh the additional effort required to build and use the underlying models. An evaluation of the FBS Linkage method following the same procedure as described in Section 4 suggests an overall improvement over CPM, as shown in Table 6. It should be noted that this evaluation again involves a degree of unavoidable subjectivity.

6. Concluding remarks

ECs and their management are crucial in engineering industries and can determine the success or failure of products. Numerous methods have been proposed in the last two decades to support ECM.

This article discussed how one of the most established methods, the CPM, was improved through a requirements-based benchmarking approach and incorporation of a FR scheme. The paper also contributes a systematic approach to assess and improve existing methods, a set of requirements for ECM methods, and a novel ECM method.

The benchmarking approach proceeded in four steps, where, first, a set of requirements for ECM methods was developed; second, these requirements were used as benchmark criteria to assess CPM as well as seven other promising ECM methods; third, the best-in-class methods for seven identified criteria where CPM was outperformed were studied to draw improvement suggestions for CPM; and fourth, to address these improvement suggestions, an enhanced ECM method known as the FBS Linkage method was developed.

The set of requirements includes 25 criteria for ECM methods which were identified drawing on the literature and industrial experience. These requirements were organised into five categories related to: (1) input, (2) model building, (3) model use, (4) output, and (5) model capabilities. They can provide guidance for improvement of current ECM methods and development of future methods.

The resulting FBS Linkage method models a design as a network of its structural, behavioural, and functional elements. The elements and connections in this network allow prediction and tracing of change propagation. The FBS Linkage method improves on CPM in the following ways: (1) it allows representation of the design at more detailed and different levels of decomposition, (2) it enables modelling of changes initiated in different aspects of the product, (3) it models the product in the context of its functions and working mechanisms, thus, improving change prediction accuracy and product modelling capability, and (4) it allows case-by-case reasoning about change propagation, thereby, supporting change containment and solution development. On the downside, the FBS Linkage model requires more information, and thus, is more complicated to prepare and use than CPM. Our experience from case study applications and an initial evaluation against the set of requirements developed in this paper suggest an overall improvement.

We recognise three limitations of our research which provide opportunities for further work. First, the comparative assessment of ECM methods involves some unavoidable subjectivity. Possibilities to extend and improve the comparative scoring of different ECM methods could be explored in future work, and a more rigorous ranking developed to support method selection in industry. Second, the developed set of requirements was not evaluated. An industrial evaluation of the requirements and the development of weighting factors for different industries, for instance, would add significant value. Third, a complete evaluation of the FBS Linkage method against the set of requirements in an industry context remains to be done.

As well as the example presented in this paper, the method has been successfully applied to a diesel engine and other applications are in the progress. At the time of writing, the method is being implemented as a module for the Cambridge Advanced Modeller software. Once this module is ready for use, we hope to undertake an industrial evaluation.

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