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Industrial evaluation of FBS Linkage – a method to support engineering change management

Bahram Hamraz[a]* and P. John Clarkson[b]

[a]*Siemens AG, Corporate Technology, Otto-Hahn-Ring 6, Munich 81739, Germany;* [b]*Department of Engineering, Engineering Design Centre, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK*

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Engineering changes (ECs) are raised throughout the product life cycle and their management can determine the commercial success of products. A well-established method to support engineering change management (ECM) is the change prediction method (CPM). The function–behaviour–structure (FBS) linkage method enhances CPM with an FBS scheme and allows more detailed modelling and analysis of ECs. The goal of this paper is to provide an industrial evaluation of the FBS Linkage method. For that purpose, we provide first an overview of the FBS Linkage method, before applying it to a diesel engine design and evaluating it by a group of 10 experienced engineers from the diesel engine manufacturer. Overall, the engineers favoured the FBS Linkage method and ranked it on average 3.7 out of 5.0 against a set of 25 different requirements for ECM methods. The evaluation underlines the benefits of the method in terms of a systematic way for capturing, explaining and transferring knowledge about the product and effects of ECs on it. Identified improvement areas include more guidelines on the scope of the method, reduction of the effort required to build FBS Linkage models, and an integration of the method into other applied systems.

Keywords: engineering change management; functional reasoning; change propagation; functional modelling

1. Introduction

Modifications to the descriptions of technical systems are referred to as engineering changes (ECs) (Wright 1997). In today's customer-driven and dynamic markets, ECs cannot be avoided entirely; they are rather the rule than the exception (Clark and Fujimoto 1991). In fact, the existence of a successful engineering system is hardly imaginable without ECs (Fricke and Schulz 2005). ECs can be triggered by the customers, the management or company's internal departments, the suppliers or partners, and by market drivers such as technology and regulation. The purposes of ECs are manifold and can be generally grouped into variation or improvement, and correction initiatives.

Over the past two decades, academic interest in engineering change management (ECM) has risen (Hamraz, Caldwell, and Clarkson 2013a). Many in-depth company case studies have been conducted to understand the current practices and issues of ECM in order to derive the needs

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*Corresponding author. Email: bh351@cam.ac.uk for future development (Jarratt et al. 2011). As a result, a variety of frameworks and tools aimed at aiding investigation, analysis, prediction of change propagation, and the management of ECs have been developed. However, ECs and their uncontrolled propagation still pose a challenge for industry. While many companies recognise ECs as being important for their businesses, very few have implemented dedicated change management tools with even fewer claiming that they can handle change issues successfully (Huang and Mak 1999; Maier and Langer 2011). Thus, further design research is required to support the practice of ECM.

In our past research at the Engineering Design Centre at the University of Cambridge, we have developed the change prediction method (CPM) in close collaboration with our industrial partners (Clarkson, Simons, and Eckert 2004). CPM models a product as a numerical network of its components and applies a stochastic algorithm to calculate the overall strength of component connections and thus the risk of change propagation between components. Successively, we have enhanced CPM by introducing a function–behaviour–structure (FBS) scheme to its product model. This method, termed FBS Linkage, models the product in greater detail and allows for more detailed analysis of ECs. While we have presented the development approach and some details of the FBS Linkage method in (Hamraz, Caldwell, and John Clarkson 2012; Hamraz et al. 2013b), an industrial evaluation still remains to be done. This is the focus of this paper at hand.

The remainder of the paper is structured as follows: Section 2 sets the background. Section 3 provides an overview of the FBS Linkage method. Section 4 presents its application to a diesel engine. Section 5 presents an evaluation of the FBS Linkage method. Finally, Section 6 summarises and concludes the paper.

2. Background

Dealing with ECs is not straightforward. Change initiated in one part of the system tends to have knock-on effects, triggering follow-up changes in other parts. This phenomenon known as *change propagation* (Terwiesch and Loch 1999; Fricke et al. 2000; Clarkson, Simons, and Eckert 2004) is very common to engineering products due to the high interconnectivity between their components. The first change in such a propagation chain is termed *initiated change* and the rest *emergent changes* (Eckert, Clarkson, and Zanker 2004). Change propagation can create a snowball effect, and in the worst case, an avalanche of change activity that may affect the whole system (Eckert, Clarkson, and Zanker 2004) and involve many partners collaborating in its development (Prasad 1997). The resulting impact can be very severe as it often entails both an increase in costs and a delay in schedules.

The Automotive Industry Action Group (AIAG 2012) reported for the North American automotive industry in total 350,000 ECs per year along with a processing cost (excluding materials and tools) of up to USD 50,000 per EC. Fricke et al. (2000) concluded from a survey with German companies that 30% of daily work of engineers and managers is related to ECs. Maier and Langer (2011) confirmed this for Danish companies based on a survey with more than 90 engineering firms from different industry sectors and sizes in Denmark. Loch and Terwiesch (1999) investigated the impact of ECs on costs and schedules and found that ECs consume 33–50% of the engineering capacity at the firm they examined along with 20–50% of tool costs.

To support ECM, many methods and tools were developed. Based on a comprehensive systematic literature survey and categorisation, Hamraz et al. (2013b) identified 54 ECM methods. These methods support knowledge representation in product design and have a fundamental goal in common: they capture tacit knowledge that is held as experience in the heads of designers and make it formal and available within the whole organisation (Chandrasegaran et al. 2013). In their core, most methods include a product model and a technique to predict and analyse the impact of change propagation. Traditional methods predominantly focus on a single product layer such as the structural or behavioural layer; they include *C-FAR* (Cohen, Navathe, and Fulton 2000), *RedesignIT* (Ollinger and Stahovich 2004), and *CPM* (Clarkson, Simons, and Eckert 2004). CPM models a product as a network of its components, quantifies the direct links between the components, and uses this numeric network to calculate the risk of change propagation between components, considering direct and several steps of indirect propagation. Some methods aim specifically at change propagation between different organisations in alliances; they include *the distributed ECM* (Chen, Shir, and Shen 2002), *the parameter-based method* (Rouibah and Caskey 2003), and *ADVICE* (Kocar and Akgunduz 2010). More recent developments have a stronger focus on multiple information layers and try to consider not only intra-layer but also cross-layer paths that change can take for propagation; they include the *pattern-based method* (Chen, Macwan, and Li 2007), the method using a *unified feature modeling scheme* (Ma, Chen, and Thimm 2008), the *multi-domain change propagation network* (Pasqual and De Weck 2012), the *Contact and Channel Model* (Albers et al. 2011), the method using the *Axiomatic Design Matrix* (Janthong 2011), the *interface representation model* (Rahmani and Thomson 2011), and the *multi-domain system network* (Van Beek and Tomiyama 2012).

The FBS Linkage method falls also in this last category, because it uses information from the three layers of structures, behaviours, and functions. Thereby, structure refers to what the product consists of, behaviour to how its constituent parts act or react in their environment, and function to what these behaviours are used for (Gero 1990). The method uses concepts from functional reasoning. Typical of functional reasoning approaches in engineering design are representational mechanisms of functional concepts together with description mechanisms of state or structure and behaviour and explanation mechanisms for functions (Far and Elamy 2005). Seminal examples include the FBS schemes from Gero and his colleagues (see, e.g. Gero 1990), Goel and his colleagues (see, e.g. Goel, Rugaber, and Vattam 2009), and Tomiyama, Umeda, and their colleagues (Umeda et al. 1990). All three schemes represent the functions, behaviours, and structure of products explicitly and model causal relations between them while avoiding hidden or implicit dependencies. They allow capturing ECs which (initially) might affect any product attribute. However, all three ontologies focus on a very granulated level of detail and have been applied primarily to products of low to medium complexity so far. Reported application examples include a gyroscope composed of 7 components (Goel, Rugaber, and Vattam 2009), a nitric-acid cooler composed of 6 components (Goel and Stroulia 1996), a copier composed of 6 components (Umeda et al. 1996), a vacuum cleaner composed of 11 components (Umeda et al. 2005), and a buzzer composed of 4 components (Qian and Gero 1996). More complex examples include a shifting system of a student racing car composed of 18 components, which in a reduced form leads already to a FBS network composed of over 100 unique elements (Van Beek, Erden, and Tomiyama 2010). While these three seminal ontologies are very useful for reasoning purposes which go beyond the analysis of change propagation, they seem to be too rigorous for complex products where change propagation is more relevant. Furthermore, the ontologies define the attributes of all three layers and elaborate their inter-layer links, but they do not specify the links between attributes of the same layer (i.e. intra-layer links). Thus, they do not provide all information needed to build a complete product network which could be used for change propagation modelling. Finally, the effort of developing the ontologies is relatively high as all attributes have to be individually identified, described, and interlinked. Though the number of structural attributes is limited, there is a high number of behavioural attributes. This is especially true for the state-transition-based ontologies from Goel and colleagues and Tomiyama and colleagues which represent behaviours as a sequence of state transitions.

In order to allow the application of FBS thinking to ECM, a modified ontology was developed for FBS Linkage (Hamraz, Caldwell, and John Clarkson 2012). This ontology adapts Gero's FBS model 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 systematic development of functional block diagrams and reduces ambiguity by providing a comprehensive dictionary of functions and flows. This dictionary helps to reconcile different notions of function, which otherwise can lead to inconsistencies while modelling the function structure of an existing design (Eckert et al. 2011). Helms, Shea, and Hoisl (2009) and Helms and Shea (2012) followed a similar approach and incorporated the functional basis into the FBS scheme from Tomiyama, Umeda, and colleagues (Umeda et al. 1990).

The requirement-based approach undertaken to develop the FBS Linkage method was presented in (Hamraz et al. 2013b). An earlier status of the method including details on the ontology and underlying assumptions and an initial application to a simplified model of a diesel engine design was presented in (Hamraz, Caldwell, and John Clarkson 2012). The next section will provide an overview of the FBS Linkage method.

3. The FBS Linkage method

The FBS Linkage method combines the concept of CPM with an FBS scheme and follows the four stages as depicted in Figure 1.

3.1. *Decompose the product*

Depending on the desired level of detail, a product 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 higher the degree of decomposition, the more information about the product can be stored and the more precisely change propagation can be modelled.

In practice, the level of detail should be chosen to suit the anticipated application of the model. For example, if the purpose of the model is to support management decisions related to price estimations and overall project planning of a requested design modification, a less detailed model would be sufficient. Such decisions are relevant, for instance, when customers ask for a modified version of a product model. To compete in the bidding process, quick high-level assessments of the change effort and required delivery time are needed. However, if the model should be used by the designers to analyse ECs and support their day-to-day decisions, a more detailed model is required. For instance, a component designer might want to know which specific attributes of his component are affected by a change.

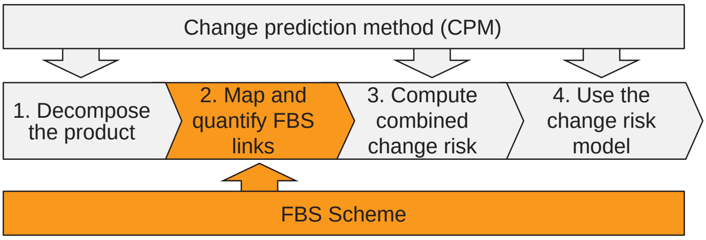


Figure 1. Concept of the FBS Linkage method (colour online).

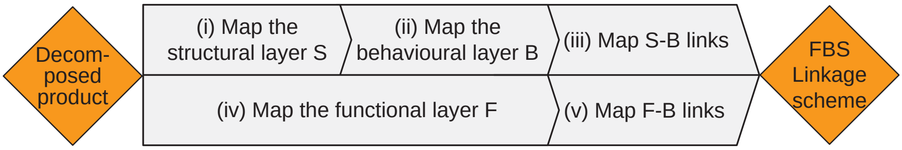


Figure 2. Step-by-step development of an FBS Linkage scheme (colour online).

3.2. *Map and quantify FBS links*

An FBS scheme can be developed for the design to be analysed following the five steps depicted in Figure 2.

For a given decomposed product, (i) structural and (ii) behavioural attributes can be defined and their elements linked to each other within each layer. For the structural layer, a number of ideally independent attributes can be considered, such as *Material* (i.e. material type, specific material properties, etc.), *Geometry* (i.e. diameters, form, shape, etc.), *Surface* (i.e. surface finish, surface properties, etc.), *Colour* (i.e. colour saturation, intensity, etc.), and *Controller* (i.e. transistors, chips, microprocessors, etc.). For the behavioural layer, different types of preferably independent behaviours should be identified, such as *Mechanical* (i.e. all behaviours to do with weight, moments of inertia, etc.), *Thermal* (i.e. all temperature- and heat-related behaviours), and *Electrical* (i.e. all behaviours to do with current, voltage, etc.).

Then, (iii) the structural elements that determine the component behaviours must be linked to each other. 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, for example, the influence of the structural attribute *Colour* on *Thermal* behaviour is often insignificant compared to the influence of *Material* on *Thermal* behaviour.

In parallel, (iv) the functional layer can be mapped as a functional block diagram composed of functions interlinked by flows of energy, material, and signal based on the reconciled functional basis (Hirtz et al. 2002). 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.

Finally, (v) to obtain the function–behaviour links, the functions can be assigned to components that realise them and then specified to responsible component behaviours.

The result is a product linkage model – *the FBS Linkage scheme*. This scheme can be represented as a network or as a corresponding multidomain matrix (MDM). As illustrated in Figure 3, the FBS Linkage network is composed of structural, behavioural, and functional elements which are linked to each other within and between the layers. This three-layered network is a more detailed product model than the flat CPM network. By explicitly considering functional, behavioural, and structural attributes of the product, the FBS Linkage method transforms a great deal of tacit knowledge into available formal knowledge. Consequently, the method enables more detailed analysis of changes because it allows investigation of changes that affect any product attribute or link. Furthermore, it models the product in the context of its functions and working mechanisms and thus enables reasoning about change propagation and supports change containment and solution development.

Next, the direct FBS links can be quantified by likelihood and impact of change propagation. This step can be either undertaken simultaneously while mapping the different network layers during the steps *(i)–(v)* or at the end when the FBS Linkage scheme is complete. Direct likelihood considers the relative frequency of change propagation between two components, and direct impact considers the relative severity of propagated changes. The change likelihood from one

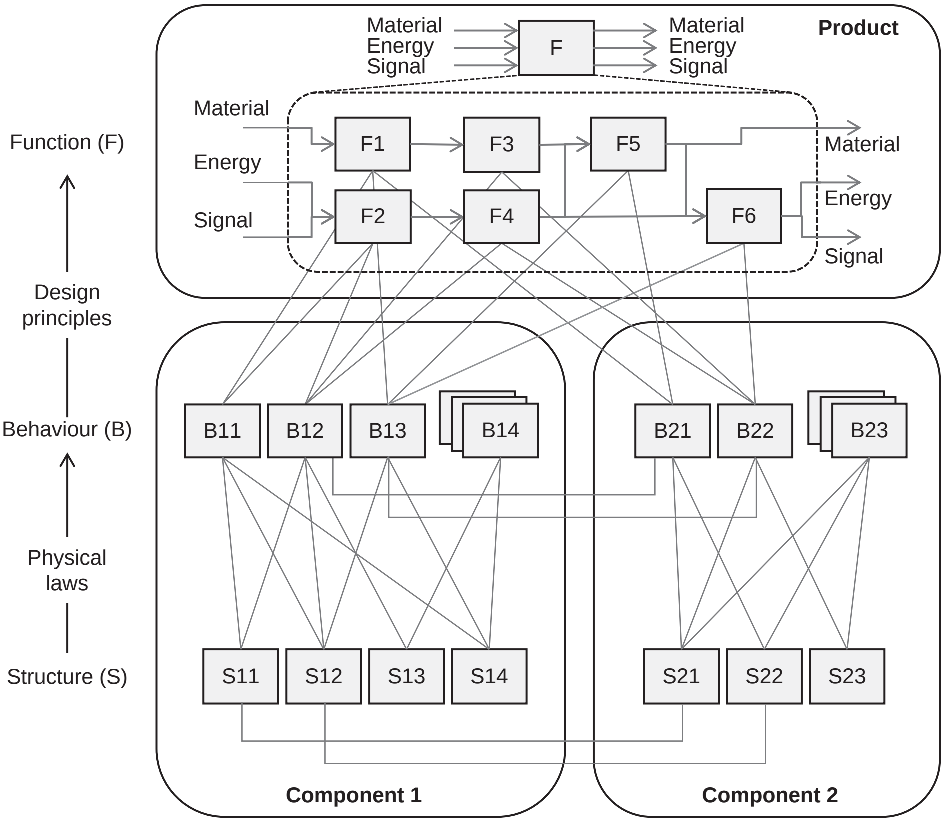


Figure 3. FBS Linkage network and the corresponding ontology assumptions.

element *E1* to another *E2* is defined as the proportion of changes to *E1* which propagate to cause change in *E2*. For instance, if every second change of *E1* causes a change in *E2*, the likelihood is 0.5. The change impact from *E1* to *E2*, on the other hand, considers the average proportion of the original design effort that would be required to modify *E2* to accommodate a change propagated from *E1*. For instance, if a propagated change from *E1* to *E2* affects one-fifth of the design of *E2*, the impact is 0.2. Both values can be elicited from experts based on their prior experience and knowledge of the product. For these estimations, the average of many possible changes (i.e. average change magnitude) and a wide range of change mechanisms and propagation paths are considered. Thus, the obtained combined risk values in the next step represent a general risk profile for the whole design, applicable to a wide range of changes. However, if a risk profile for a specific change of a given element with a given magnitude is required, the direct change likelihood and impact values between that element and its direct neighbours could be determined more accurately and replace the generic values.

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. 2013c). 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.

In general, each link between two elements could be quantified individually and separately for each direction. However, to minimise this tedious task of quantifying the available links one by one, three shortcuts can be taken: (1) the values of many links can be assumed as symmetric; (2) the links between the structural and behavioural elements which are mostly independent from the components can be quantified collectively first and then changed for exceptions; and (3) some other links can be quantified by standard values if they have not been specified yet, for example, 0.5 for likelihood and 0.3 for impact. The remaining links can be quantified using three different values, for example, 0.3 for low, 0.5 for medium, and 0.8 for high. To estimate these values, the relations between directly linked attributes can be investigated for generic changes. The network representation is more useful for this step.

3.3. *Compute combined change risk*

Combined risk of change propagation is the sum of direct and indirect risk, where d*irect 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 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. The combined risk of change propagation is calculated using the *Forward CPM* algorithm, which considers how change can propagate between any pair of elements through multiple direct and indirect paths. In overview, the algorithm operates by applying intersection and union operators along the change propagation paths to calculate path likelihoods and impacts while excluding self-dependencies and cyclic paths. Full details of the equations are provided in (Simons 2000; Clarkson, Simons, and Eckert 2004; Keller 2007). The algorithm is implemented in the freely available software program *Cambridge Advanced Modeller* (CAM) (Wynn et al. 2010).

3.4. *Use the model*

The FBS Linkage scheme shows how the product's structure is organised to exhibit actual behaviours which realise its functions. The outcome can be applied for both qualitative and quantitative analysis of the design and change propagation. The qualitative FBS network 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 allow 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, the FBS network can be used to investigate which elements should be manipulated to accommodate the functional change most effectively. The quantitative results could be applied to analyse change propagation. The focus of the model is the product domain. Other domains such as design process, organisation, manufacturing and supply chain could be incorporated into the model for a more comprehensive management of ECs.

4. Application to a diesel engine design

The engine modelled here is Perkins' VistaD diesel engine as partly discussed in (Jarratt, Eckert, and Clarkson 2004; Keller, Eckert, and Clarkson 2009; Hamraz, Caldwell, and John Clarkson 2012). The definition of different types of links in the existing CPM model helped to map and quantify the structural and behavioural layers of the FBS Linkage model. The functional layer and the inter-layer links were developed additionally with support from Tom W. Ridgman, a diesel engine expert from the Institute for Manufacturing at the University of Cambridge. Mr Ridgman has worked in the automotive industry for 20 years, in a variety of roles in new product development, manufacturing strategy and operations, including more than 5 years in the diesel engine product development of Perkins.

The FBS Linkage model for the diesel engine was built following the steps described in Section 3. For the quantification of the links, existing CPM models of the engine were used in combination with further assumptions as described below for the additional links that were not part of those CPM models. As the focus of this study was to evaluate rather the whole method than the fidelity of diesel engine model, in this study, standard values were assumed for those additional links. These values seem reasonable for an initial model of the engine but may be further refined to improve the confidence of the output.

4.1. *Decompose the diesel engine*

The diesel engine was decomposed into 42 components (Table 1).

4.2. *Map and quantify FBS links*

(2i) Map the structural layer S: The four structural attributes *Geometry* (*Ge*), *Material* (*Ma*), *Surface* (*Su*), and *Controller* (*Ct*) were used to define (42·4 =) 168 structural elements. The structural links between these elements were drawn and quantified from existing CPM models of the engine.

Table 1. Component decomposition of the diesel engine.

No.	Component	No.	Component
1	Cylinder head assembly	22	Crank pulley damper belt
2	Cylinder block assembly	23	Fan drive
3	Piston rings gudgeon pin	24	Fan extension
4	Conn rod	25	Coolant pump
5	Crankshaft main bearings	26	Alternator bracket
6	Valve train	27	Belt-driven auxiliary (hydraulic pump)
7	Cam shaft	28	Gear train
8	Push rods	29	Gear-driven auxiliary (compressor)
9	High-pressure fuel pipes	30	Timing case
10	Electric control module	31	Balancer
11	Fuel pump	32	Turbocharger
12	Fuel injection assembly	33	Aircharge cooler
13	Adapter plate/flywheel housing	34	Air intake
14	Flywheel ring gear	35	Air filter
15	Starter motor	36	Exhaust manifold
16	Sump	37	Low-pressure fuel system
17	Oil filler	38	Fuel filter
18	Engine breather	39	Starting aid
19	Oil pump	40	Lifting eyes
20	Oil filter	41	Wiring harness
21	Oil cooler	42	Radiator

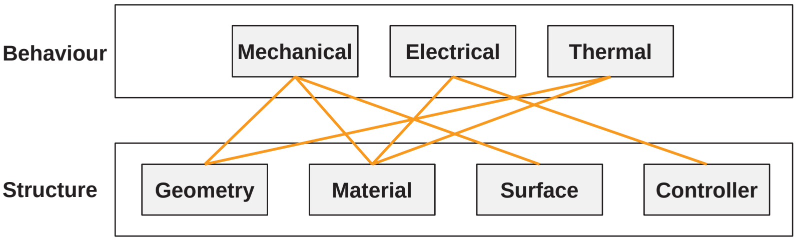


Figure 4. Defining the links between the structural and behavioural attributes of the diesel engine (colour online).

(2ii) Map the behavioural layer B: Similarly to the structural elements, $(42 \cdot 3 =)$ 126 behavioural elements were defined using the three behavioural attributes: *Mechanical* (*Me*), *Electrical* (*El*), and *Thermal* (*Th*). The behavioural links between these elements were drawn and quantified from existing CPM models of the engine.

(2iii) Map the structure-behaviour (S-B) links: The links between the structural and behavioural elements were identified collectively and symmetrically for all corresponding elements using the attribute relations depicted in Figure 4. If the attribute link was not relevant on the element level, it was removed subsequently. These links were quantified using standard values of 0.5 for change likelihood and 0.1 for change impact. The likelihood value of 0.5 assumes that only half of all changes are critical enough to propagate and the impact value of 0.1 assumes that the re-design effort required to accommodate propagated changes amounts 10% of the initial design effort. These assumptions seem reasonable as initial values for a collective quantification of all existing links and may be refined for individual links as the model evolves.

(2iv) Map the functional layer F: The functional model of the diesel engine was developed by applying the reconciled functional basis from Hirtz et al. (2002) to detail the four diesel strokes. Forty subfunctions were identified and interlinked by flows of material, energy, and signal (Figure 5).

Fuel, air, oil, exhaust gases, and piston were used as material flows. The flows of energy were differentiated into thermal, electrical, rotational, translational, pneumatic, hydraulic, acoustic, and vibrational. Signal includes the interaction with the engine user in order to start the engine and control its speed. Although the functional block diagram in Figure 5 is directed, it was considered to be undirected for change propagation because changes can propagate forwards and backwards along the flows. These links were quantified using one of three standard values for change likelihood (i.e. 0.3 for low, 0.5 for medium, and 0.8 for high likelihood) and 0.1 for all change impact values.

The functional model follows most of the proposed functions and flows from the reconciled functional basis. However, in some cases, it was decided to be more precise, and in other cases, less precise. For example, on the one hand, while Hirtz et al. (2002) used general functions such as *Import liquid*, it was decided to use here a more precise function description such as *Import fuel* to locate subfunctions. On the other hand, functions such as *Start engine* (*F1*) are kept less detailed than suggested by the reconciled functional basis because their elementary level is less relevant for the change model of the diesel engine.

(2v) Map the function-behaviour (F-B) links: The functional elements (subfunctions) were first linked to the components and then further specified into undirected links between functional and behavioural elements. As with the S-B links, these links were quantified using standard values of 0.5 for change likelihood and 0.1 for change impact.

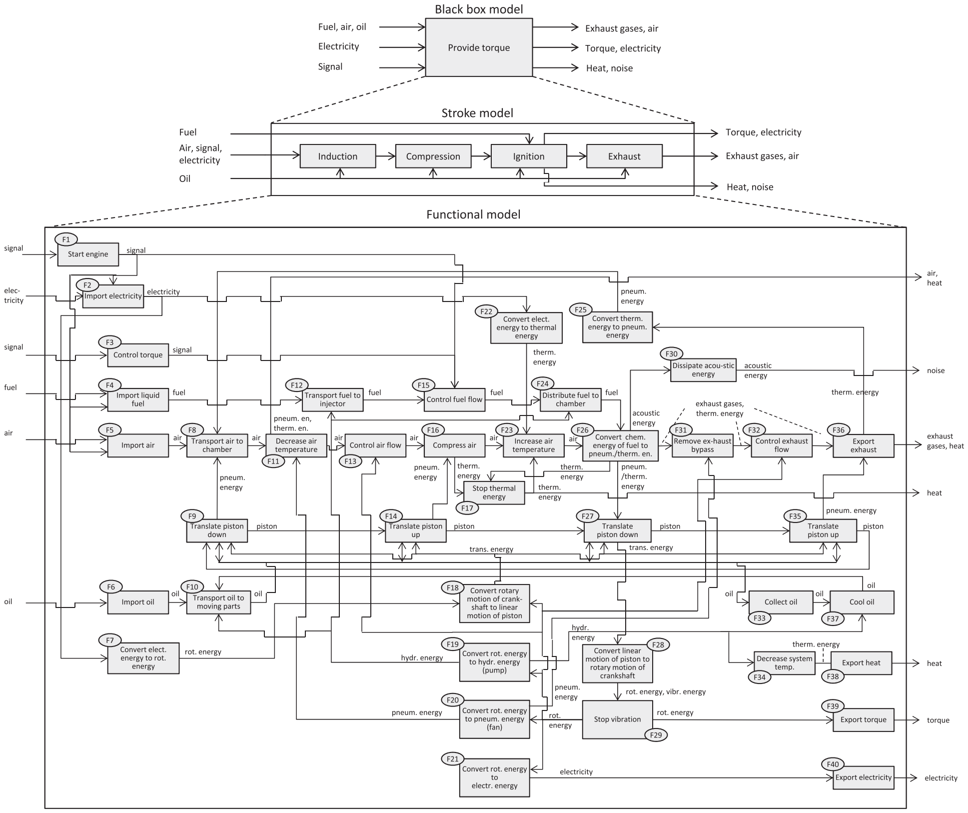


Figure 5. Functional elements and links of the diesel engine.

4.3. *Compute combined change risk*

Finally, all links and elements were put together to complete the FBS Linkage scheme for the diesel engine. This network was imported into the CAM software and the Forward CPM algorithm was applied to calculate the combined risk profile considering six steps of propagation. The detailed results are represented in the risk MDM in Figure 6. The shading colour indicates the risk value: the darker (redder) the cells, the higher the risk. Although, the diagram resolution is too low for reading the details, the screenshot indicates the density distribution of the MDM.

4.4. *Use the model*

The combined risk MDM in Figure 6 shows the dependencies between the functional, behavioural, and structural layers in multiple attribute dimensions and can help understand how changes propagate within the system. It is more populated than the direct likelihood or impact MDMs and has only a few empty cells because it combines direct and indirect connections.

For high-level analyses, the behavioural and structural layers of the combined risk MDM were aggregated using the maximum operator ($=\max\{\}$) to obtain the component–component risk design structure matrix (DSM) in Figure 7. This aggregated matrix includes the maximum combined risk values of the three behavioural and four structural attribute design structure matrices (DSMs) as well as the 24 square domain mapping matrices (DMMs) between them as depicted in Figure 6. Thus, this result represents the worst-case scenario of change propagation; the

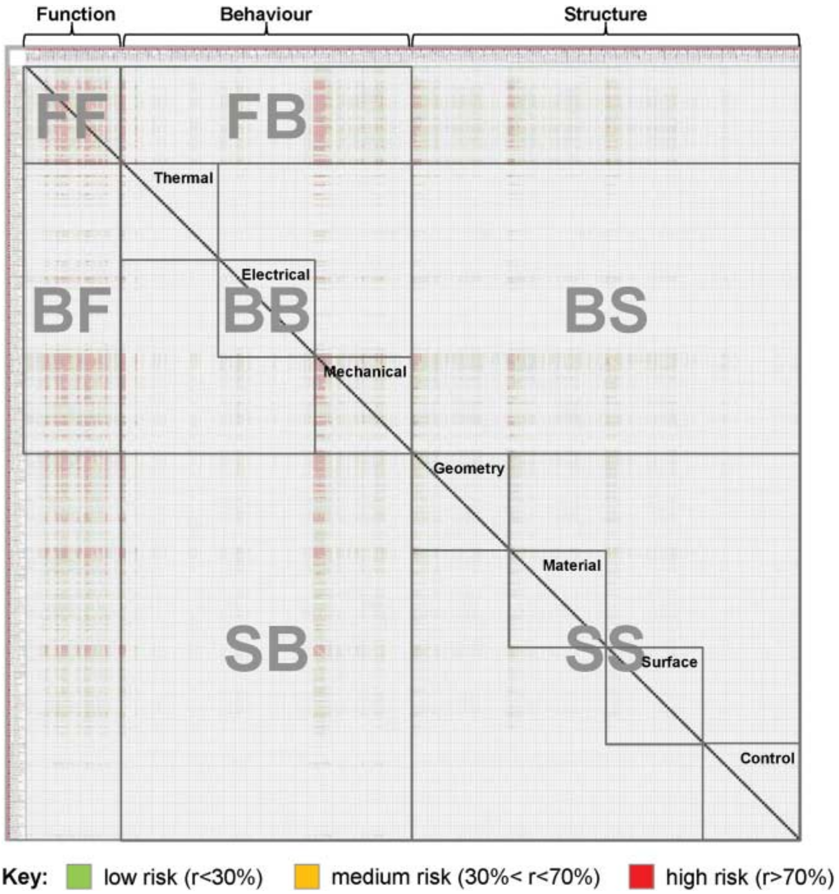
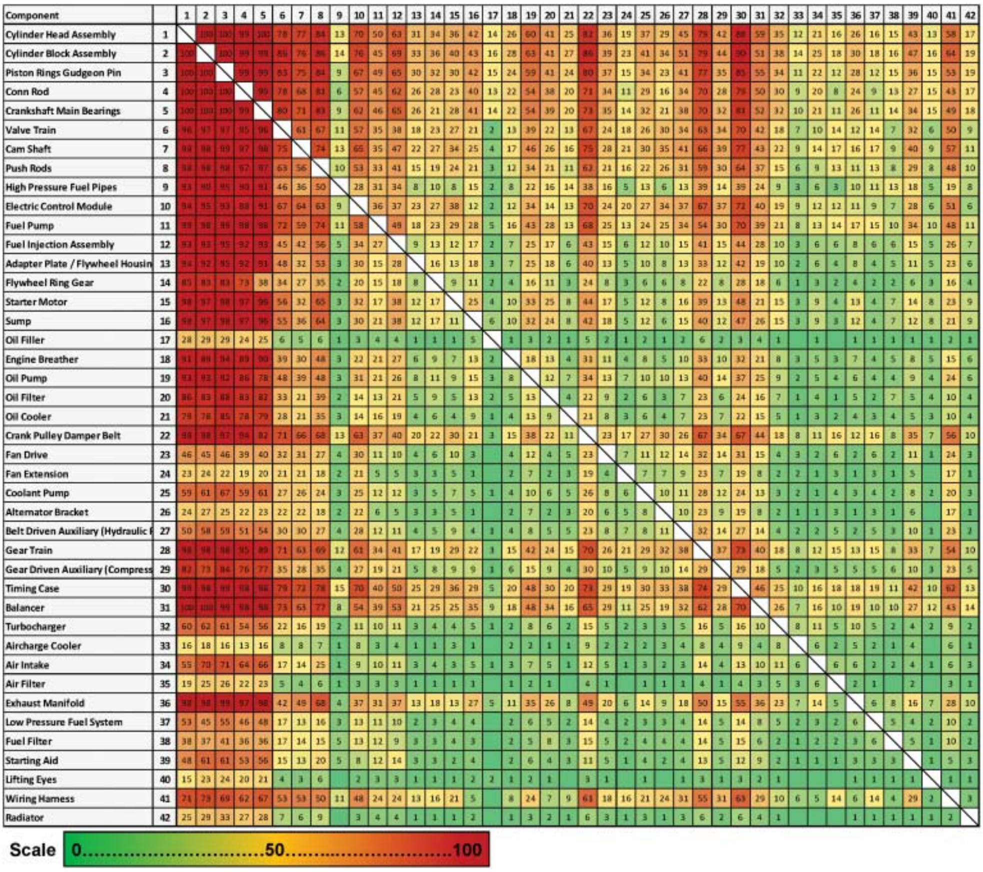


Figure 6. Combined risk MDM for the diesel engine (colour online).

DSM does not differentiate between the types of change (e.g. *Geometry*, *Material*, or *Electrical* behaviours) and assumes that all component attributes are affected simultaneously while taking the highest risk into account. Such a DSM helps to identify risk absorbers and multipliers (Eckert, Clarkson, and Zanker 2004) and compare the component risk profiles to each other (Keller, Eckert, and Clarkson 2009).

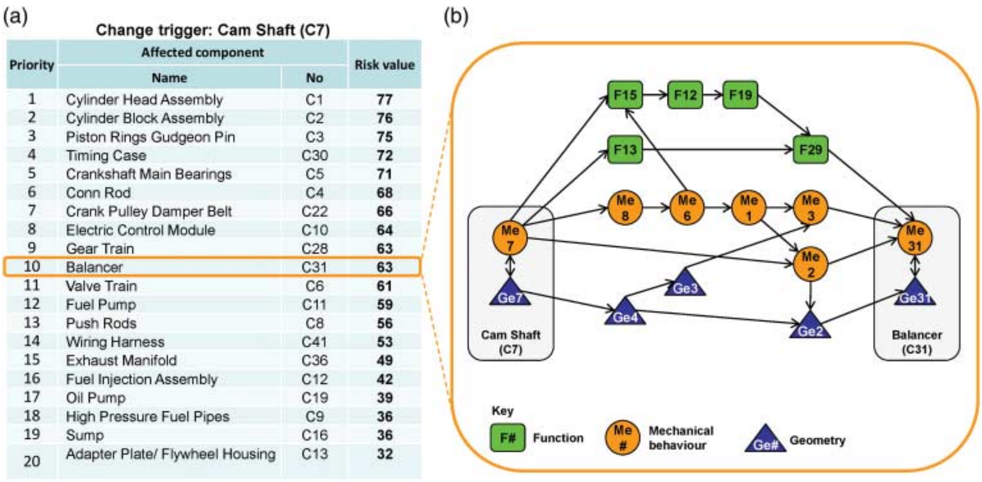
The colour scale indicates the risk values as follows: Green is used for low risk, yellow for medium risk, and red for high risk. The overall average of the risk values is 24.9%, with a distribution of {min; 0.25-quantile; median; 0.75-quantile; max} = {0; 5%; 14%; 34%, 100%} and a population-density (i.e. actual risk values above zero divided by possible links) of 98.3%. The distribution is right-skewed and the majority of the links have low risk values. The colour scale of Figure 7 indicates that the components *C1–C12* are critical towards receiving changes from other components (i.e. rows 1–12) as well as imposing changes to other components (i.e. columns 1–12) and especially among each other (cells within rows and columns 1–12). This result is expected because these components form the engine core and include the majority of connectivity in the engine. The links between most of the other components (C13–C42), which are rather peripheral components, are less critical. The high population density of this DSM reflects the view that the whole diesel engine is one fully integrated system and suggests that all components are interlinked to each other. A change in one component may affect almost any other component.



Component		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Cylinder Head Assembly	1		100	100	99	100	78	77	84	13	70	50	63	31	34	36	42	14	26	60	41	25	82	36	19	37	29	45	79	42	88	59	35	12	21	16	26	16	15	43	13	58	17
Cylinder Block Assembly	2	100		100	99	99	86	76	86	14	76	45	69	33	36	40	43	16	28	63	41	27	86	39	23	41	34	51	79	44	90	51	38	14	25	18	30	18	16	47	16	64	19
Piston Rings Gudgeon Pin	3	100	100		99	99	83	75	84	9	67	49	65	30	32	30	42	15	24	59	41	24	80	37	15	34	23	41	77	35	85	55	34	11	22	12	28	12	15	36	15	53	19
Conn Rod	4	100	100	100		99	78	68	83	6	57	45	62	26	28	23	40	13	22	54	38	20	71	34	11	29	16	34	70	28	79	50	30	9	20	8	24	9	13	27	15	43	17
Crankshaft Main Bearings	5	100	100	100	99		80	71	83	9	62	46	65	26	21	28	41	14	22	54	39	20	73	35	14	32	21	38	70	32	83	52	32	10	21	11	26	11	14	34	15	49	18
Valve Train	6	96	97	97	95	96		61	67	11	57	35	38	18	23	27	21	2	13	39	22	13	67	24	18	26	30	34	63	34	70	42	18	7	10	14	12	14	7	32	6	50	9
Cam Shaft	7	98	98	99	97	98	75		74	13	65	35	47	22	27	34	25	4	17	46	26	16	75	28	21	30	35	41	66	39	77	43	22	9	14	17	16	17	9	40	9	57	11
Push Rods	8	98	98	98	97	97	63	56		10	53	33	41	15	19	24	21	3	12	34	21	11	62	21	16	22	26	31	59	30	64	37	15	6	9	13	11	13	8	29	8	48	10
High Pressure Fuel Pipes	9	93	90	95	90	91	46	36	50		28	31	34	8	10	8	15	2	8	22	16	14	38	16	5	13	6	13	39	14	39	24	9	3	6	3	10	11	13	18	5	19	8
Electric Control Module	10	94	95	93	88	91	67	64	63	9		36	37	23	27	38	12	2	12	34	14	13	70	24	20	27	34	37	67	37	72	40	19	9	12	12	11	9	7	28	6	51	6
Fuel Pump	11	99	98	99	98	98	72	59	74	11	58		48	18	23	29	28	5	16	43	28	13	68	25	13	24	25	34	54	30	70	39	21	8	13	14	17	15	10	34	10	48	11
Fuel Injection Assembly	12	93	93	95	92	93	45	42	56	5	34	27		9	13	12	17	2	7	25	17	6	43	15	6	12	10	15	41	15	44	28	10	3	6	6	8	6	6	15	5	26	7
Adapter Plate / Flywheel Housin	13	94	92	95	92	93	48	32	53	3	30	15	28		16	13	18	3	7	25	18	6	40	13	5	10	8	13	33	12	42	19	10	2	6	4	8	4	5	11	5	23	6
Flywheel Ring Gear	14	85	83	83	73	38	34	27	35	2	20	15	18	8		9	11	2	4	16	11	3	24	8	3	6	6	8	22	8	28	18	6	1	3	2	4	2	2	6	3	16	4
Starter Motor	15	98	97	98	97	96	56	32	65	3	32	17	38	12	17		25	4	10	33	25	8	44	17	5	12	8	16	39	13	48	21	15	3	9	4	13	4	7	14	8	23	9
Sump	16	98	97	98	97	96	55	36	64	3	30	21	38	12	17	11		6	10	32	24	8	42	18	5	12	6	15	40	12	47	26	15	3	9	3	12	4	7	12	8	21	9
Oil Filler	17	28	29	29	24	25	6	5	6	1	3	4	4	1	1	1	5		1	3	2	1	5	2	1	2	1	2	6	2	3	4	1		1		1	1	1	1	1	2	1
Engine Breather	18	91	89	94	89	90	39	30	48	3	22	21	27	6	9	7	13	2		18	13	4	31	11	4	8	5	10	33	10	32	21	8	3	5	3	7	4	5	8	5	15	6
Oil Pump	19	93	93	92	86	78	48	39	48	3	31	21	26	8	11	9	15	3	8		12	7	34	13	7	10	10	13	40	14	37	25	9	2	5	4	6	4	4	9	4	24	6
Oil Filter	20	86	83	88	83	82	33	21	39	2	14	13	21	5	9	5	13	2	5	13		4	22	9	2	6	3	7	23	6	24	16	7	1	4	1	5	2	7	5	4	10	4
Oil Cooler	21	79	78	85	78	79	28	21	35	3	14	16	19	4	6	4	9	1	4	13	9		21	8	3	6	4	7	23	7	22	15	5	1	3	2	4	3	4	5	3	10	4
Crank Pulley Damper Belt	22	98	98	97	94	82	71	66	68	13	63	37	40	20	22	30	21	3	15	38	22	11		23	17	27	30	26	67	34	67	44	18	8	11	16	12	16	8	35	7	56	10
Fan Drive	23	46	45	46	39	40	32	31	27	4	30	11	10	4	6	10	3		4	12	4	5	23		7	11	12	14	32	14	31	15	4	3	2	6	2	6	2	11	1	24	3
Fan Extension	24	23	24	22	19	20	21	21	18	2	21	5	5	3	3	5	1		2	7	2	3	19	4		7	7	9	23	7	19	8	2	2	1	3	1	3	1	5		17	1
Coolant Pump	25	59	61	67	59	61	27	26	24	3	25	12	12	3	5	7	5	1	4	10	6	5	26	8	6		10	11	28	12	24	13	3	2	1	4	3	4	2	8	2	20	3
Alternator Bracket	26	24	27	25	22	23	22	22	18	2	22	6	5	3	3	5	1		2	7	2	3	20	6	5	8		10	23	9	19	8	2	1	1	3	1	3	1	6		17	1
Belt Driven Auxiliary (Hydraulic F	27	50	58	59	51	54	30	30	27	4	28	12	11	4	5	9	4	1	4	8	5	5	23	8	7	8	11		32	14	27	14	4	2	2	5	2	5	3	10	1	23	2
Gear Train	28	98	98	98	95	89	71	63	69	12	61	34	41	17	19	29	22	3	15	42	24	15	70	26	21	29	32	38		37	73	40	18	8	12	15	13	15	8	33	7	54	10
Gear Driven Auxiliary (Compress	29	82	73	84	76	77	35	28	35	4	27	19	21	5	8	9	9	1	6	15	9	4	30	10	5	9	10	14	29		29	18	5	2	3	5	5	5	6	10	3	23	5
Timing Case	30	99	98	99	98	98	79	72	78	15	70	40	50	25	29	36	29	5	20	48	30	20	73	29	19	30	33	38	74	29		46	25	10	16	18	18	19	11	42	10	62	13
Balancer	31	100	100	99	98	98	73	63	77	8	54	39	53	21	25	25	35	9	18	48	34	16	65	29	11	25	19	32	62	28	70		26	7	16	10	19	10	10	27	12	43	14
Turbocharger	32	60	62	61	54	56	22	16	19	2	11	10	11	3	4	4	5	1	2	8	6	2	15	5	2	3	3	5	16	5	16	10		8	11	5	10	5	2	4	2	9	2
Aircharge Cooler	33	16	18	16	13	16	8	8	7	1	8	3	4	1	1	3	1		2	2	1	1	9	2	2	2	3	4	8	4	9	4	8		6	2	5	2	1	4		6	1
Air Intake	34	55	70	71	64	66	17	14	25	1	9	10	11	3	4	3	5	1	3	7	5	1	12	5	1	3	2	3	14	4	13	10	11	6		6	6	2	2	4	1	6	3
Air Filter	35	19	25	26	22	23	5	4	6	1	3	3	3	1	1	1	1		1	2	1		4	1		1	1	1	4	1	4	3	5	3	6		2	1		2		3	1
Exhaust Manifold	36	98	98	99	97	98	42	49	68	4	37	31	37	13	18	13	27	5	11	35	26	8	49	20	6	14	9	18	50	15	55	36	23	7	14	5		6	8	16	7	28	10
Low Pressure Fuel System	37	53	45	55	46	48	17	13	16	3	13	11	10	2	3	4	4		2	6	5	2	14	4	2	3	3	4	14	5	14	8	5	2	3	2	6		5	4	2	10	2
Fuel Filter	38	38	37	41	36	36	17	14	15	5	13	12	9	3	3	4	3		2	5	8	3	15	5	2	4	4	4	14	5	15	6	2	1	2	2	3	6		5	1	10	2
Starting Aid	39	48	61	61	53	56	15	13	20	5	8	12	14	3	3	2	4		2	6	4	3	11	5	1	4	2	4	13	5	12	9	2	1	1	1	3	3	3		1	5	3
Lifting Eyes	40	15	23	24	20	21	4	3	6		2	3	3	1	1	1	2	2	1	2	1		3	1		1		1	3	1	3	2	1				1	1	1	1		1	1
Wiring Harness	41	71	73	69	62	67	53	53	50	11	48	24	24	13	16	21	5		8	24	7	9	61	18	16	21	24	31	55	31	63	29	10	6	5	14	6	14	4	29	2		3
Radiator	42	25	29	33	27	28	7	6	9		3	4	4	1	1	1	2		1	3	2	1	6	3	1	3	1	3	6	2	6	4	1				1	1	1	1	1	2	

Scale 0……………………………50……………………………100

Figure 7. Aggregated combined risk DSM for the diesel engine (FBS Linkage) (in %) (colour online).



(a)

Change trigger: Cam Shaft (C7)

Priority	Affected component		Risk value
	Name	No	
1	Cylinder Head Assembly	C1	77
2	Cylinder Block Assembly	C2	76
3	Piston Rings Gudgeon Pin	C3	75
4	Timing Case	C30	72
5	Crankshaft Main Bearings	C5	71
6	Conn Rod	C4	68
7	Crank Pulley Damper Belt	C22	66
8	Electric Control Module	C10	64
9	Gear Train	C28	63
10	Balancer	C31	63
11	Valve Train	C6	61
12	Fuel Pump	C11	59
13	Push Rods	C8	56
14	Wiring Harness	C41	53
15	Exhaust Manifold	C36	49
16	Fuel Injection Assembly	C12	42
17	Oil Pump	C19	39
18	High Pressure Fuel Pipes	C9	36
19	Sump	C16	36
20	Adapter Plate/ Flywheel Housing	C13	32

Figure 8. (a) Prioritised change risk list for Cam Shaft and (b) selected change propagation paths from Cam Shaft to Balancer (colour online).

This combined risk DSM of the FBS Linkage method can be used as a starting point of the change propagation investigation. For every component, a prioritised list of all affected components can be prepared based on this DSM. Every line in that list can then be further detailed and the risk numbers can be traced back to causal propagation paths on the attribute level using the FBS Linkage MDM and network. For instance, Figure 8(a) shows such a prioritised change risk list for *Cam Shaft (C7)*. From the list, it can be seen that *Cylinder Head (C1)* and *Block Assembly (C2)* and *Piston-Rings-Gudgeon-Pin (C3)* are at highest risk if the *Cam Shaft* changes. Usually, the components at high risk are closely interconnected to the change trigger and the impact on them is preeminent to designers. However, the links to the components in the middle range of the risk values are not always obvious because these components are usually only indirectly connected. Such a prioritised list can help avoid oversight of change impacts on those components. Figure 8(b) details the links between *Cam Shaft* (C7) and *Balancer (C31)*. This propagation path analysis provides a rationale for the risk value and explains how the change trigger affects the target.

5. Evaluation

An evaluation workshop was conducted at Perkins Engines Company Limited in Peterborough with 10 engineers. An overview of the participants, their positions, and their years of experience is presented in Table 2.

The first author presented the method and demonstrated the corresponding model to the industry experts. All experts were new to the method. Engineer I was involved in the development of the original CPM in 2004. All the others had not come across the CPM. Questions raised during the presentation were answered, and ambiguities and open issues were clarified to ensure that the experts sufficiently comprehended the method. Then, they were asked to verbally assess the method. The workshop took two hours and was recorded completely. The recordings were transcribed and analysed to abstract the key arguments. The evaluation results were sent to the participants by e-mail to allow them to revise any possible transcription errors and to ensure that their arguments were considered completely and correctly.

Representatively for the evaluation, a few quotes are presented here:

Engineer I, who supported the development and testing of the original CPM from the Perkins side, commented:

> This is a combination of robust engineering, functional models, boundary elements, understanding the linkages, and understanding of energy flows which is fundamental but not well understood. Generating this model teaches you how the product works. ‘How does the energy flow?’, ‘What goes on in there?’ And then you can understand what happens to all interfaces. This model basically – very nicely, especially since you brought the FBS side into it – gives you the user experience understanding [. . .] and it links into the structural behaviour and flow of energy, so you can understand how does thermal energy leave from the combustion system to flow through the structure and how likely is it that it will have an effect on this component over here. Why that is so critical is that a change over here affects a component over there – and it is not intuitive.

Table 2. Interview participants.

Participant	Current position	Experience in years
Engineer A	Design & Development Engineer	2
Engineer B	Manufacturing Engineer	9
Engineer C	Engineering Black Belt	10
Engineer D	Component Engineering Department Manager	13
Engineer E	CAD System & Drawing Release Supervisor	17
Engineer F	BOM & Configuration Engineer, Team Leader	20
Engineer G	Technical Resource Manager, Product Validation	22
Engineer H	Cost Reduction Program Manager	23
Engineer I	Delegated Final Assembly Manager, Technical Steward	Over 20
Engineer J	Technical Resource Manager for Core Components	Over 40

Engineer J commented:

> Like FMEAs, this actually enables people with less experience to pull on the experience from everybody else. The real value of this in my mind is that, if this is done upfront with a team of absolute experts, so it’s there. Then as the program explodes, everybody can jump in there immediately and get it.

Engineer A continued:

> If you do it right the first time, you save valuable management time. [. . .] Once you got a network, you could use it on several platforms. [. . .] You still have to come back to adapt it to other platforms, and the changes between two different platforms could be dramatically. However, this reduces the number of required experts in the subsequent meetings. Instead of calling all the experts, you can call only the experts that are needed for the specific components [. . .] and have smaller meetings.

Engineer H commented:

> It just points you in a direction. For me, once you get something like that [a list of affected components] and it looks a bit strange, then I go, ‘well, that’s actually not what I expected. what’s driving that?’ This is effectively what an FMEA does anyway. I don’t hang up on the accuracy of the number. The number is not irrelevant but it’s the principle.

Engineer G added:

> That is what we would get from the boundary diagrams in combination with the FMEAs. And that’s exactly how we should structure our FMEAs with reference to those structures. The only bit that it doesn’t give you is the quantified bit. It just says that these things are connected, you should consider it.

Engineer B noted:

> I think we are also worrying a bit too much about how we apply it to our daily business, right here and right now, and how we start using it, [. . .] rather than, as a model, would it work if you had something simpler.

Engineer C concluded:

> As a method to reduce the required experience needed, I definitely say that the concept is working.

Engineer D explained:

> When you get to a very complex system such as an engine, the model starts to get very, very big, and the required resources to update and maintain it get very, very big. It comes to a point, where ‘does the return value justify the amount of input?’ It’s not like that we haven’t got something that does at least some part of the job. But when you shrink it down to a system like a Turbocharger or an Oil Pump I wonder if it has more value. Then, you could do it in more detail. You can be very much more specific.

Engineer E said:

> I think it would be good to see such a model integrated on top of our existing PLM systems. I think that would be an ideal situation. [. . .] So we would be able to understand, ‘ok, I am changing this part, it’s going to have a risk on these particular parts’.

Engineer J stated:

> I think one of the key things is the generation of the model. I am not sure how sophisticated it is, but I mean it can be quite complicated, requiring a lot of understanding. The simpler it is to create, the more likely it is to be used.

Engineer A added:

> Maybe a software can facilitate this, with an interface that would break it down.

Table 3. Overview of the key arguments of the industry experts about the FBS Linkage method.

No.	Argument	Exhibits
Praised advantages		
a1	Provides a checklist of things to consider and avoids oversight	Engineer D: ‘When you are doing a change, this provides a checklist. So, “I am doing a change and this is the checklist of things I should consider”’ Engineer H: ‘I look at that [the list of affected components by a change to the Cam Shaft] and I think, “I am surprised that the Fuel Pipes would be impacted by the Cam Shaft”. What it does give me is something to go and look at’ Engineer A: ‘I think this method transits us from an open problem, where the experts have to identify the boundaries, to a closed problem, where we can fix exactly the whole process so that we don’t have anything missing from the whole list’
a2	Captures and transfers knowledge	Engineer J: ‘Like FMEAs, this actually enables people with less experience to pull on the experience from everybody else. The real value of this in my mind is that, if this is done upfront with a team of absolute experts, so it’s there. Then as the program explodes, everybody can jump in there immediately and get it’ Engineer C: ‘As a method to reduce the required experience needed, I definitely say that the concept is working’
a3	Shows how the product works	Engineer J: ‘This is a combination of robust engineering, functional models, boundary elements, understanding the linkages, and understanding of energy flows which is fundamental but not well understood. Generating this model teaches you how the product works’
a4	Can be adapted to other platforms	Engineer A: ‘If you do it right the first time, you save valuable management time. [. . .] Once you got a network, you could use it on several platforms’
a5	Improves current practice and processes	Engineer D: ‘I think the method is good. It is going to provoke a few thoughts and a few discussions about our existing processes, at the very least, and plus a few ideas about the future maybe’ Engineer G: ‘There are some ideas that we can reuse on our existing processes’
Suggested improvements		
b1	Rather than modelling the whole product, the method could focus on systems only and be more specific	Engineer D: ‘I worry that even at 42 systems [for the diesel engine] it doesn’t give you enough detail to tell you exactly what action you should take [. . .]. At the end of the day, a lot of our inefficiency is not necessarily on the Cylinder Block or the Cylinder Head or the Conn Rod – we don’t necessarily make the mistakes there. It’s quite often on the smaller parts that one might classify as the less complex components. [. . .] But when you shrink it down to a system like a Turbocharger or an Oil Pump I wonder if it has more value. Then, you could do it in more detail. You can be very much more specific’

(*Continued*)

Table 3. Continued

No.	Argument	Exhibits
		Engineer C: ‘I think the problem is the scope because there are so many things you can change’
b2	The amount of effort to build the model could be reduced	Engineer E: ‘You probably have got a degree of risk in having too many experts being involved in this’ Engineer G: ‘There is an awful amount of effort and meetings to put numbers against it. [. . .] If you were to reapply that to our current engines, it would take significantly more effort, because you’ve got more components and more complexity, and now you’ve got also software control systems [. . .] and changing functions dependent on what the engine seeks’ Engineer J: ‘I think one of the key things is the generation of the model. I am not sure how sophisticated it is, but I mean it can be quite complicated, requiring a lot of understanding. The simpler it is to create, the more likely it is to be used’ Engineer A: ‘Maybe a software can facilitate this [generation of the model], with an interface that would break it down’
b3	The method could be integrated to other systems to allow regular update	Engineer E: ‘I suspect the risk that you might have with this model is that this is going to be outdated in the early project phase. The question is, “is it going to be revisited and revised continuously?” [. . .] I think it would be good to see such a model integrated on top of our existing PLM systems. I think that would be an ideal situation’

Engineer D concluded:

> I think the method is good. It is going to provoke a few thoughts and a few discussions about our existing processes, at the very least, and plus a few ideas about the future maybe.

Engineer G added:

> There are some ideas that we can reuse on our existing processes. I’d like to think that we could go to a full model at some point, but I think to release the resources for that, you would have to demonstrate, what is the outcome value of this to justify the upfront resources.

To summarise the evaluation, the first author read through the manuscript and abstracted the arguments to create a separate list of distinct arguments for each expert. Then, the arguments were compared among the experts, and similar ones were clustered. For the clusters, a comprehensive description was generated by combining or rephrasing the arguments. The result is presented in Table 3, where the arguments are categorised into ‘praised advantages’ or ‘improvement suggestions’ and exhibits are provided by corresponding quotes from the engineers. As can be seen from this overview, the advantages of the FBS Linkage method that the industry experts praised include its capability to: (1) provide a checklist, (2) capture and transfer knowledge, (3) show how the product works, (4) be adapted to other platforms, and (5) improve current practice and processes. However, there are also a number of limitations that they pointed out and that need to be considered in the future improvement of the method. The main issues to be addressed include: (1) the scope of the method might be narrowed allowing it to be more specific for systems, (2) the amount of effort to build the model could be reduced, and (3) the method could be integrated to other systems in order to be updated regularly.

Table 4. Rating of the FBS Linkage method against requirements.

Engineer		A	B	C	D	E	F	G	H	J	Ø
Experience in years Requirement	Description	2	9	10	13	17	20	22	23	> 40	
1. Range of products covered	Allows manageable modelling of a variety of different products, from low to high complexity	4	4	5	4	4	4	3	4	4	4.0
2. Range of levels of decomposition covered	Allows modelling of the whole product on different levels of decomposition (i.e. system, component, part, attribute)	5	4	5	4	4	4	4	4	4	4.2
3. Range of different changes covered	Allows modelling of changes from different kinds, that is, domains, life cycle time, purpose, initiator, cause, target, and considers the change magnitude	4	3	4	4	3	5	4	4	4	3.9
4. Ease of model building	The model-building procedure is easy, that is, it can be done by any practitioner if an appropriate manual is provided	2	3	2	2	2	3	3	4	1	2.4
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.)	3	3	1	4	3	3	4	4	4	3.2

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	3	3	4	4	4	5	4	3	2	3.6
7. Accuracy	The model captures all relevant dependencies explicitly and avoids hidden and implicit dependencies between product attributes	4	3	3	2	4	4	3	4	4	3.4
8. Consistency	The model-building approach supports consistency checks, ensuring that the model is internally consistent and consistent with other models	5	4	4	4	4	4	3	4	2	3.8
9. Adaptability	A model of an existing product can be adapted to analyse a new product, that is, existing models can be re-used easily	4	4	4	4	3	4	3	3	4	3.7
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)	4	3	4	2	4	5	2	5	3	3.6
11. Ease of model use	The use of the model is easy, that is, it can be used by any designer if an appropriate manual is provided	4	4	4	4	3	4	2	4	3	3.6

(*Continued*).

Table 4. Continued

Engineer		A	B	C	D	E	F	G	H	J	Ø
Experience in years Requirement	Description	2	9	10	13	17	20	22	23	> 40	
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	3	4	4	4	4	5	4	3	3	3.8
13. Practicality	The approach is applicable to a real situation and effective in use	4	4	4	4	4	4	3	4	4	3.9
14. Flexibility	The model can easily be changed/updated	3	2	4	3	4	4	3	4	2	3.2
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)	4	4	5	2	3	3	2	5	2	3.3
16. Utility of results	Provide useful analysis for different users (i.e. at different levels of detail) and depict results clearly	5	2	4	4	4	4	3	4	4	3.8
17. Quantity of results	Provide sufficient and complete analyses	5	4	4	2	3	4	3	4	4	3.7
18. Quality of results	Provide correct and accurate results (difficult to assess!)	5	4	3	3	4	4	3	4	4	3.8
19. Product modelling capability	Descriptively model the product to represent and improve product understanding and support product improvement and communication	4	4	4	5	4	4	4	5	5	4.3
20. Change modelling capability	Descriptively model change impacts	5	2	4	3	4	4	4	4	4	3.8

21. Change prediction capability	Predict changes caused by change propagation	5	4	2	4	4	4	4	4	4	3.9
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	5	3	4	4	4	4	4	5	5	4.2
23. Solution finding capability	Enable development and testing of alternative solutions and support the solution selection process	4	3	5	3	3	3	3	4	3	3.4
24. Numerical analysis capability	Allow numerical and probabilistic change prediction and risk analysis	5	4	5	4	4	4	3	5	4	4.2
25. Compatibility	Support integration with other tools	3	2	5	4	3	4	3	3	4	3.4
Unweighted average (Ø)		4.1	3.4	3.9	3.5	3.6	4.0	3.2	4.0	3.5	3.7

Note: Engineer I had to leave the workshop earlier and did not complete the questionnaire.

At the end of the workshops, the experts were given a questionnaire including 25 requirements for ECM methods and their descriptions, and they were asked to rate the method against the requirements using a scale from 1 to 5 as follows: 1 (strongly disagree), 2 (disagree), 3 (neither agree nor disagree), 4 (agree), and 5 (strongly agree). These requirements were developed and discussed in (Hamraz et al. 2013b), following five steps: First, publications describing 54 ECM methods were reviewed to draw a long list of requirements from literature. Second, requirements based on case-study experience were added to the list. Third, the resulting long list of requirements from both literature and case studies was studied to identify and remove duplicates and produce a list of unique requirements. Forth, a contextual framework consisting of the five requirement categories related to *Input*, *Output*, *Change propagation method*, *Modeller*, and *User* was developed and the list of unique requirements was organised into these five categories. Finally, the list of organised requirements was reviewed and further adjusted and completed to obtain the 25 requirements.

A summary of the assessment results is given in Table 4.

The assessment results in Table 4 show that overall the experts agree that the FBS Linkage method meets the requirements (unweighted average score: 3.7 out of 5.0). Overall, the result of this survey is in line with the verbal evaluation during the workshop. In principle, the engineers favour the FBS Linkage method. The requirements they ranked the highest are: *19. Product modelling capability* (4.3), *3. Range of levels of decomposition covered* (4.2), *22. Change containment capability* (4.2), and *24. Numerical analysis capability* (4.2). These advantages are related to the level of detail modelled by the FBS Linkage method and to the numerical approach undertaken to estimate risk profiles. However, with respect to the following requirements, they are relatively reserved: *4. Ease of model building* (2.4), *5. Availability of information to build the model* (3.2), and *14. Flexibility* (3.2). These limitations are concerned about the complexity and effort required to develop a model.

This interview and questionnaire-based assessment is indicative and subject to expert opinions. A few limitations of this assessment should be emphasised here. To reduce subjectivity, only external evaluators who were not involved in model building were selected. The evaluation was solely based on the method details presented to the experts by the first author during the workshop. These details were presented in form of slides and elaborated the modelling approach and the generated output as partly presented in Sections 3 and 4. As a result, some of the requirements which are related to working directly with the model and applying it to actual tasks were assessed based on limited evidence. Model verification (i.e. is it correct?) was undertaken throughout the model-building process, but was not explicitly covered in this workshop. However, the experts were presented with diagrams of all three layers of the FBS network including the functional block diagram and had time to comprehend the logic and check for plausibility and completeness before they judged the method and completed the questionnaire. In this context, it should be noted that the assessment could also be distorted because of the influence of the presentation itself on the evaluation. Furthermore, the assessment was performed in the presence of the author. This allowed the experts to ask questions and clarify any issues they had with the questionnaire or the understanding of the method, but anonymity was not provided. Thus, the experts may have been intimidated by the author and assessed the method more positively.

Overall, the evaluation was insightful and helped to reveal strengths and weaknesses of the method and laid the foundation for further improvement. However, it can only be considered as an early stage of model validation and does not replace an evaluation based on an actual implementation in practice and application on real data. That way, not only the feasibility and performance of the tool can be evaluated but also its usability in real-life conditions. Further validation of the method in industry would be required and will be part of our future work.

6. Summary and conclusion

ECs are essential and their management can determine the commercial success of products. To support ECM, the FBS Linkage method was developed. This method enhances the approved concept of CPM by introducing an FBS scheme into its product model. Essentially, this enhancement enables modelling the product in greater detail and allows for more detailed analysis of changes.

This paper aimed at providing an industrial evaluation of the method to pave the way for further improvement directions. To do so, first, the FBS Linkage method was outlined, before it was applied to model a diesel engine design. Then, a workshop was conducted with 10 engineers from the diesel engine manufacturer to evaluate the method.

Overall, the engineers favoured the FBS Linkage method and ranked it on average 3.7 out of 5.0 against a set of 25 different requirements for ECM methods. However, the experts pointed out some areas for further improvements as well. They praised the method's capabilities to: (a1) provide a checklist of change affected parts and thereby ensure that nothing is missed out, (a2) capture and transfer knowledge from experts to the whole organisation, (a3) show how the product works and promote a better understanding of the system interactions, (a4) be adapted to other platforms, and (a5) improve current practice and processes of ECM. However, there are also a number of limitations that the practitioners pointed out and that need to be considered in the future improvement of the method. (b1) The engineers advised to reconsider the scope of the method and pointed out that although it would be good to model the whole product, it might be even more useful for such a method to focus only on one system and model it more precisely to provide more specific guidance. (b2) They warned about the amount of input and effort required to build FBS Linkage models and suggested to find out ways to simplify or reduce it. (b3) Furthermore, they suggested that the method could be linked to other systems in order to be regularly updated and integrated into the applied systems. These issues will be addressed in our future work. To recommend an optimal scope of the method (i.e. b1), models of different levels of granularity could be assessed against each other in terms of cost and benefit. Furthermore, the sensitivity of the model output to its input could be investigated to make a recommendation on the amount and quality of input information required for a cost-benefit optimised model. To reduce the model-building effort (i.e. b2), the method will be fully implemented into the software program CAM. This software tool would facilitate further case studies and help continuous improvement and industrial acceptance of the method. The software tool could then be gradually enhanced to increase automation in model building. The diesel engine model presented in this paper was manually built and mostly created from scratch. The required information was gathered from technical product documentations and expert interviews. Techniques which facilitate or even partly automate information gathering and model building can significantly reduce the model-building effort. These may include knowledge-based techniques which use information from existing models to support building of new models as well as automated reading and analysing of technical documents. In this context, building a repository of FBS Linkage models may be very helpful. It could be investigated whether the (reconciled functional basis) Design Repository of the Design Engineering Lab at Oregon State University could be used for this purpose. Finally, to investigate how the method could be linked to other systems (i.e. b3), more research must be conducted to identify possible interfaces between FBS Linkage and product life cycle management software and determine interface requirements for the integration. Furthermore, the dimensions of the model – functions, behaviours, and structures – could be extended to incorporate other domains such as organisation, design process, manufacturing and factory requirements, and supply chain. These additional layers play an important role in companies with significant production rates and would allow a more comprehensive analysis of EC propagation.

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