FBS Linkage ontology and technique to support engineering change management

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Abstract - Engineering changes are essential for any product development and their management has become a crucial discipline. Research in engineering change management has brought about some methods and tools to support dealing with changes. This work extends the Change Prediction Method (CPM) through incorporation of a Function-Behaviour-Structure (FBS) scheme. These additional levels of detail provide the rationales for change propagation and allow a more pro-active management of changes. First, we develop the ontology of this method based on a comprehensive comparison of three seminal functional reasoning schemes. Then, we demonstrate the FBS Linkage technique by applying it to a diesel engine. Finally, we evaluate the method.

Keywords – engineering change management, change prediction, functional reasoning, multi-domain model

List of Acronyms

CAM – the Cambridge Advanced Modeller
CPM – the Change Prediction Method
DMM – domain mapping matrix
DRM – the Design Research Methodology
DSM – design structure matrix
EC – engineering change
FBS – function-behaviour-structure
FBSta – the Function-Behaviour-State framework
FBStr – the Function-Behaviour-Structure framework
FR – functional reasoning
MDM – multidomain matrix
SBF – the Structure-Behaviour-Function framework
SEM – scanning electron microscope

1 Introduction

Heraclitus, a Greek philosopher known for his doctrine of change as a central phenomenon to the universe, stated around 500 BC that the only constant is change. For engineering products, this is probably truer today than ever before. Engineering changes (ECs) are raised throughout the product lifecycle and can cause severe profit losses if not managed sufficiently (Fricke et al. 2000; Maier and Langer 2011). This is because they propagate and impact all drivers of competitiveness – time, cost, and quality. As product development times are continuously decreased, the management of such changes is becoming more important (Jarratt et al. 2011). Yet still EC propagation is neither clearly understood nor is the management of changes sufficiently supported.

This paper presents our continued effort in the development of the FBS Linkage method – a multi-domain EC propagation method using the concepts of the function-behaviour-structure (FBS) schemes (e.g. Gero 1990; Goel and Chandrasekaran 1989; Umeda et al. 1990) and the change prediction method (CPM) (Clarkson et al. 2004). The additional levels of detail, namely functions, behaviours, and structures, and their relations provide the rationales for change propagation and allow a more pro-active management of changes. Pro-active EC management comprises the five guidelines from Fricke et al. (2000): reduce the number of changes, detect changes earlier, authorise changes more effectively, implement changes more efficiently, and continuously improve the management of changes.

In prior work, we introduced the concept of the *FBS Linkage* model and proved its feasibility and merit using a diesel engine example (Hamraz et al. 2012a, b). However, we did not detail the ontology of the FBS Linkage method to provide a uniform framework for developing models, and we did not elaborate the technique of building an FBS Linkage model. These two shortcomings will be addressed in this paper. We will present the ontology and the modelling technique and apply them to build an enhanced model for the diesel engine. Finally, we will evaluate the method.

The remainder of this article is structured in five sections. Section 2 provides the background to this research. Section 3 presents the FBS Linkage method. Section 4 applies this method to a diesel engine and discusses its results. Section 5 evaluates the method, and finally, Section 6 concludes this article.

2 Background

2.1 Engineering change management

Engineering change (EC) can be defined as “changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behaviour (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behaviour (design principles), or behaviour and structure (physical laws) of a technical artefact” (Hamraz et al. 2013a). The terms structure, behaviour, and function are used as defined by (Gero and Kannengiesser 2004): Structure defines, what an artefact is; behaviour describes, what it does; and function prescribes, what it is for. Change propagation is the term used to refer to the domino-effect of ECs. Due to the interrelations between constituent parts of engineering product, a single change to one part usually has knock-on effects on other parts and causes additional changes. This change snowballing might take different patterns and in worst case lead to an avalanche which never comes to an end without intervention (Eckert et al. 2004). Thereby, ECs significantly influence the development time, cost, and quality. Different reports suggest that ECs use around one third of the engineering design capacity (Ahmed and Kanike 2007; Fricke et al. 2000; Maier and Langer 2011). Therefore, the management of ECs is essential. It can be well compared with fire safety and fighting measures dealing with the five guidelines “less”, “earlier”, “more effective”, “more efficient”, and “better” (Fricke et al. 2000). These guidelines suggest that: first, the occurrence of changes should be avoided as far as possible; second, changes should be detected as early as possible to reduce their impact; third, changes should be selected more effectively and fourth, implemented more efficiently. Finally, the organisation should learn from past changes to continuously improve the management of ECs.

2.2 Engineering change methods

To stick with the fire safety and fighting analogy above, EC methods and tools can be compared with the fire safety and fighting equipment (e.g. fire alarm, engine, extinguisher). They aim to support EC management in different phases. Many methods and tools have been proposed in the last ten years. Seminal methods on which many others have built initially appeared on the scene in the early 2000s and are C-FAR (Cohen and Fulton 1998; Cohen et al. 2000), CPM (Clarkson et al. 2001b, 2004), RedesignIT (Ollinger and Stahovich 2001; Ollinger and Stahovich 2004). A comprehensive review can be found in (Jarratt et al. 2011) and will not be repeated here, but rather up-dated with recent developments in multi-domain methods.

Pasqual and de Weck (2011) proposed a multi-domain change propagation network model including the domains *product, change (process)*, and *social*. Thereby, the product domain is a network of the components, the change domain a network of change requests, and the social domain a network of people. For the analysis of changes within this network, they proposed a repository of existing tools and metrics including two new metrics. Ahmad et al. (2011b) proposed a method that tracks changes across four domains using an *information structure framework* which links requirements to functions, functions to components, components to the detailed design process. Rahmani and Thomson (2011; 2012) proposed an interface representation model and implemented it in a Java based software. Their tool helps linking product data from multiple engineering domains and classifying and representing interfaces in a structured format. It improves the information sharing and coordination between collaborating design teams and can be used to support the management of cross-domain and cross-discipline changes. Albers et al. (2011) implemented their *Contact and Channel Model (C&CM)* in the *Cambridge Advanced Modeller (CAM)* software environment (for an introduction to CAM, see e.g. Wynn et al. 2010). Their tool supports the modelling of functional interrelations between function and form and helps reveal the links between functional requirements and the physical parts on multiple levels of abstraction. Their model can support change prediction analysis in combination with CPM (Boerstring et al. 2008). Janthong (2011) used the *Axiomatic Design Matrix (DM)* which maps the domains of design parameters to functional requirements to estimate the effects of changes. The use of DM to trace and analyse design changes was suggested in earlier work from (Guenov and Barker 2005). Fei et al. (2011a; 2011b) proposed a modelling method which helps to trace change propagation within and between the functional requirement domain and the physical structure (i.e. components) domain. Van Beek and Tomiyama (2012) presented a multi-domain system network including the product use domain, the function, behaviour, state domains, and the stakeholder domain. They suggest that this cross-domain network can be used to facilitate the management of ECs. Their work extends their initial approach as presented by Van Beek et al. (2010), which applied graph theory principles to the *Function-Behaviour-State* model from Umeda and Tomiyama (1997) and aimed to support modularisation. Koh et al. (2012) proposed *CPM-HoQ* for assessing change options with respect to their impact on customer requirements. Their method builds on the concepts of *CPM* and *House of Quality* and integrates the domains of components and requirements.

2.3 Functional reasoning ontologies

Functional reasoning (FR) deals with theories and techniques aimed at explaining and deriving functions of artefacts. This research stream's roots go back to early work from Sembugamoorthy and Chandrasekaran (1986). Since then, many FR approaches have been developed to support design tasks (for an overview, see (Umeda and Tomiyama 1997) and (Chandrasekaran 2005)). FR approaches in engineering design are distinguished by representational mechanisms of functional concepts, description mechanisms of structure or state and possibly behaviour, and explanation mechanisms for functions (Far and Elamy 2005). An excellent and very comprehensive review of FR schemes can be found in (Erden et al. 2008).

Independently from each other, three research groups developed FR schemes which include three domains – functions, behaviour, and structure or state. The first group from Georgia Institute of Technology guided by Goel extended the hierarchical representation of artefact's functions and behaviours from Sembugamoorthy and Chandrasekaran (1986) into the *Structure-Behaviour-Function (SBF)* model and proposed a number of tools based on it (see e.g. Goel et al. 2009). The second group from University of Sydney led by Gero developed the *Function-Behaviour-Structure (here: FBStr)* framework based on Gero's earlier work on design representation (see e.g. Qian and Gero 1996). The third group from the University of Tokyo directed by Tomiyama and Umeda developed the *Function-Behaviour-State* (here: *FBSta*) modelling and a conceptual design-support tool called Function-Behaviour-State Modeler based on it (see e.g. Umeda et al. 1996). Thereby, State is a generalised concept of structure (Umeda et al. 1990).

3 FBS Linkage method

3.1 Incorporation of a FBS scheme to CPM

CPM uses a model of the dependencies between component pairs to model change propagation and compute the overall risk of change propagation imposed on other components if one component changes (Clarkson et al. 2004). CPM assumes that a change to one component can only propagate to another component if they are directly linked to each other (i.e. direct change propagation) or if there is a path between them leading over several intermediary components (i.e. indirect change propagation). This assumption is essential, not only for CPM but for most existing propagation methods. It allows the use of network models to describe change propagation.

However, CPM stays only at the component level and does not provide more details of how changes propagate from one component to another. We hypothesise that CPM can be improved by detailing its component network to a more sophisticated attribute network.

According to (Gero and Kannengiesser 2004) (p. 374), *"A designer constructs connections between the function, behaviour and structure of a design object through experience. Specifically, the designer ascribes function to behaviour and derives behaviour from structure."* Such a FBS scheme may be represented as a multilayer network composed of functional, behavioural, and structural attributes, and the attribute connections can be used to describe how changes propagate between the network elements: A change to one FBS element might impact other elements if they are directly or indirectly related to each other. Thus, for a FBS scheme, it can be assumed analogous that: *changes can only propagate between structural, behavioural, and functional elements along available links in the FBS scheme.*

This assumption enables the integration of a FBS scheme into CPM by replacing the component network of CPM with a FBS network. The CPM technique proceeds with quantifying the component links in terms of likelihood and impact of change propagation. Change likelihood accounts for the frequency of how often a change propagates. Change impact accounts for the severity of how much of the initial effort has to be reinvested to implement the propagated change. Both are estimations elicited from experts based on their experience and product knowledge. In case of existing designs, the estimations can be backed up with historic data. However, the expert input is inevitable not only for new designs, where historic data is not available, but also because some changes might have never occurred in the past but need to be anticipated for the future. The product of likelihood and impact is defined as risk of change propagation. The links in the FBS network may be quantified similarly. Consequently, the Forward CPM algorithm may be applied to this numerical FBS network to compute the combined risk of change propagation. Combined refers to the sum of direct and indirect risk.

In a similar way as the FBStr concept can be used to model the design process from early stages of design (see e.g. (Gero and Kannengiesser 2004), this method can be applied already in the conceptual stage, where information about functional requirements is available but the structure is incomplete; and the designer proceeds by linking functions to behaviours and behaviours to structures to determine the FBS network. Thus, in the early design phases, the FBS network is incomplete and evolves. For the method here, this means, in early design stages where the network is incomplete, change propagation can only be described within the already existing parts of the network. This allows the method to be used to assess the impact of adding new elements to the network on the existing elements. Apart from the CPM application, the FBS network opens the door to a number of possible applications to support designers at different phases of product development, from conceptual design, over embodiment design, to detail design and throughout the product life cycle. These applications include improving understanding of the overall system and its functions, facilitating communication between engineers of different disciplines, explanation mechanisms of functions and means to promote the use of computers within design, and a better understanding of the overall design process (Erden et al. 2008).

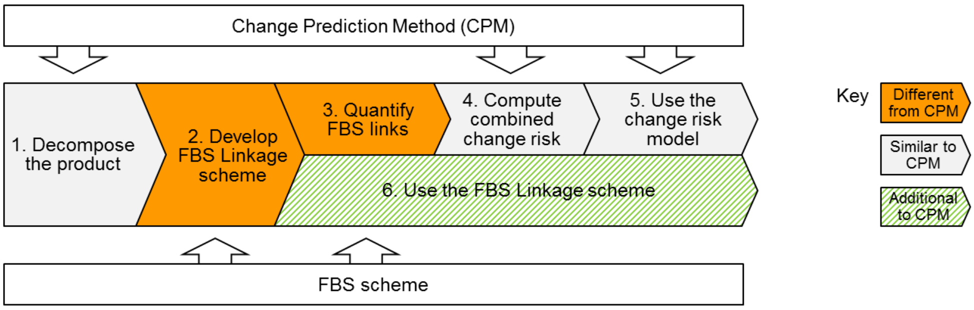


Figure 1: Stages of the FBS Linkage method

In overview, the FBS Linkage method proceeds, in six stages as depicted in Figure 1, including three similar stages to CPM (i.e. 1. Decompose the product, 4. Compute combined change risk, and 5. Use the change risk model), two modified stages (i.e. 2. Develop FBS Linkage scheme and 3. Quantify FBS links instead of Map and quantify component links) and one additional stage (i.e. 6. Use the FBS Linkage scheme) which can be in parallel with stages 3, 4, and 5.

The core of the FBS Linkage method is the FBS Linkage scheme. To specify this scheme, first, the ontologies of the three seminal FBS schemes are thoroughly reviewed and compared in the context of change propagation analysis in the next section. Then, a modified ontology for the FBS Linkage method is developed in Section 3.3.

3.2 Comparison of the ontologies of SBF, FBSta, and FBStr

It is important to notice that although SBF, FBSta, and FBStr have many aspects in common, their purpose is different. While the SBF and FBSta schemes are focused on explaining the mechanisms of products, the FBStr scheme is more concerned with explaining the design process based on the function-behaviour-structure thinking. This difference reflects in their ontologies. Ontology is used as defined by Gero and Kannengiesser (2007, p. 379) as *"structured conceptualizations of a domain in terms of a set of entities in that domain and their relationships, [which] provide uniform frameworks to identify differences and similarities that would otherwise be obscured."*

Table 1 includes a detailed comparison of these three schemes structured according to the three layers structure, behaviour, function, and the two joining spheres between structure and behaviour, and behaviour and function. This comparison shows that all three ontologies agree on causal links from structure over behaviour to function and avoid direct links from structure to function. Furthermore, they agree on the view of function as the teleology of the object. However, they incorporate different representation forms: SBF represents functions in state transition schema, FBSta in a "to do" form and FBStr in a more general "verb object" form. The differences for behaviour are more significant. SBF refers to behaviour as causal processes of artefacts (internal behaviours) that result in its functions, whereas behaviour in FBSta stands for output behaviours of an artefact of which its functions are an abstracted subset. Gero's FBStr, on the other hand, refers to behaviour as the properties of structural elements. Also in terms of structure they differ significantly. SBF represents structure by components, substances (i.e. material and abstract physical quantities), and relations between both, where component specifications contain, in addition to attributes, their primitive functions. FBSta represents structure as entities (referring to components and abstract physical quantities such as “paper weight”), their attributes, and relations. The notion of state in FBSta (where the term state comprises enduring structure plus temporary state) highlights the instantaneous character of structure and implies its changes of state through behaviours. FBStr on the other hand does not include abstract physical quantities in the structural description.

Table 1: Comparison of the SBF, FBSt, and FBS ontologies

Ontology	**Structure-Behaviour-Function (SBF)**	**Function-Behaviour-State (FBSta)**	**Function-Behaviour-Structure (FBStr)**
Main publi-cations	• (Sembugamoorthy and Chandrasekaran 1986) • (Goel and Chandrasekaran 1989) • (Goel and Stroulia 1996) • (Goel et al. 2009)	• (Umeda et al. 1990) • (Umeda et al. 1996) • (Umeda and Tomiyama 1997) • (Van Beek et al. 2010)	• (Gero 1990) • (Gero et al. 1992) • (Qian and Gero 1996) • (Rosenman and Gero 1998) • (Gero and Kannengiesser 2004) • (Vermaas and Dorst 2007)
Function	**Key distinction:** state transition schema **Definition:** *“Functions in SBF describe the role that an Element plays in the overall operation of a device. They express the purpose or goal of the Element, whereas the Behavior describes how the purpose is accomplished”* (Goel et al. 2009, p. 26). Functions are represented as a schema that specifies their pre-conditions, post-conditions, the behaviour that accomplishes the function, and possibly conditions under which the specified behavior achieves the given function (Goel et al. 2009). **Example** (Goel et al. 2009, p. 24): • Function: transfer angular momentum • Pre-condition: angular momentum magnitude Li • Post-condition: angular momentum magnitude Lo • By behaviour: transfer angular momentum	**Key distinction:** “to do” form **Definition:** Function is *"a description of behavior abstracted by human through recognition of the behavior in order to utilize it. […] in general, [functions are] represented in the form of ‘to do something’”* (Umeda et al. 1990, p. 183). **Examples** (Umeda et al. 1996, p. 277): • to make a sound • to generate light	**Key distinction**: “verb object” form **Definition:** *“Function (F) variables: describe the teleology of the object, i.e. what it is for”* (Gero and Kannengiesser 2004, p. 374). *“A function may be a physical function, such as ‘providing sufficient space’, or a non-physical function such as ‘providing an ambience’”* (Rosenman and Gero 1998, p. 169, 170). **Examples** (Gero and Kannengiesser 2004, p. 381): The functions of a window are: • enhancing winter solar gain • controlling noise • providing view • providing daylight
Links betw. Function and Be-haviour	**Key distinction**: rational, one-to-one relation *“The representation of a function of a device also includes a pointer to the internal behavior of the device that results in the function”* (Goel and Stroulia 1996, p. 360). *“Each Element in an SBF Model has a Function, and each Function has a corresponding Behavior”* (Goel et al. 2009, p. 28).	**Key distinction**: rational, subjective (designer’s choice), many-to-many relation *“The relationships between functions and behaviors are subjective and many-to-many correspondent”* (Umeda et al. 1996, p. 276).	**Key distinction**: rational, subjective (designer’s choice), many-to-many relation *“Specifically, function is ascribed to behavior by establishing a teleological connection between the human’s goals and observable or measurable effects of the object”* (Gero and Kannengiesser 2007, p. 380). *“...one function may correspond to many behaviors and one behavior may be associated with more than one function”* (Qian and Gero 1996, p. 291).

Ontology	**Structure-Behaviour-Function (SBF)**	**Function-Behaviour-State (FBSta)**	**Function-Behaviour-Structure (FBStr)**
Beha-viour	**Key distinction:** internal behaviours/ sequence of state transitions **Definition:** *"The "B" in a SBF device model refers to the internal behaviors of the device that specify how the structure of the device delivers its functions, or, in general, its output behaviors"* (Goel and Stroulia 1996, p. 356). *"A behavior is represented as a sequence of states and transitions between them"* (Goel et al. 2009, p. 25). *"SBF models use an ontology of primitive functions based on the component–substance ontology, which enables a more precise specification of state transitions in a behaviour"* (Goel et al. 2009, p. 26). **Example** (Goel et al. 2009, p. 25): • Behaviour: transfer angular momentum • State 1: momentum at gyroscope with magnitude M_input • Transition by using function: "allow angular momentum of linkage gyroscope-worm wheel" • State 2: momentum at pivot with magnitude L_ww	**Key distinction**: output behaviours/ sequence of state transitions **Definition:** *"Introducing a discrete unit time, we define behavior as "sequential state transitions along time," and assume that physical phenomena determine behavior of an entity"* (Umeda et al. 1996, p. 276). **Examples** " (Umeda et al. 1996, p. 276, 277): • hitting a bell • oscillating a string • a lamp lighting • a battery generating electricity	**Key distinction:** derivable attributes **Definition:** *"Behaviour (B) variables: describe the attributes that are derived or expected to be derived from the structure (S) variables of the object, i.e. what it does"* (Gero and Kannengiesser 2004, p. 374). *"A behaviour is thus a description of the object's actions or processes in given circumstances"* (Rosenman and Gero 1998, p. 169). **Examples** (Gero and Kannengiesser 2004, p. 381): The behaviours of a glass are: • thermal conduction • light transmission • direct solar gain
Links betw. Beha-viour and Structure (State)	**Key distinction**: causal, objective (by physical laws) Many-to-many relation *"Each component plays a functional role in a state transition in one or more internal behaviors of the device; […] A component may also be affected by some state transition"* (Goel and Stroulia 1996, p. 379). *"Causal explanations for state transitions may include physical laws, mathematical equations, functions of its subsystems, structural constraints, other behaviors, or a state or transition in another behaviour"* (Goel et al. 2009, p. 25).	**Key distinction**: causal, objective (by physical laws), In general, many-to-many relation. Within one view/aspect: one (behaviour)-to-many (states) relation *"However, a transition from a state to the next state [i.e. a behaviour] does not occur at random but is governed by some principles; viz. physical laws"* (Umeda et al. 1990, p. 183). *"However, representations of behavior may differ depending on the physical situations of the current interest. […] To represent this difference, we introduce aspects. An aspect is a collection of all relevant entities, attributes, relations, and physical phenomena of the current interest"* (Umeda et al. 1996, p. 276).	**Key distinction**: causal, objective (by physical laws) Many-to-many relation. *"Behavior is causally connected to structure, that is, it can be derived from structure using physical laws or heuristics"* (Gero and Kannengiesser 2007, p. 380). *"Similarly [to the links between functions and behaviors], behavior can be derived from more than one structure"* (Qian and Gero 1996, p. 291).
Structure or state	**Key distinction:** components, substances (i.e. physical quantities), and relations **Definition:** *"In SBF models, structure is represented in terms of components, the substances contained in the components, and*	**Key distinction:** defined state of entities (components, physical quantities), their attributes, and relations **Definition:** The state of an entity is defined by *"a set of entities, a set of attributes, and a set of relations"* amongst them (Umeda et al.	**Key distinction:** elements (components), structural attributes, and relations **Definition:** *"The structure specifies what elements the design is composed of, what the attributes of the elements are, and how*

Ontology	Structure-Behaviour-Function (SBF)	Function-Behaviour-State (FBSta)	Function-Behaviour-Structure (FBStr)
	connections among the components. The specification of a component includes its functional abstractions” (Goel et al. 2009, p. 24). *“Each component has one or more primitive functions relative to the substances: allow, move, pump, create, destroy, or expel”* (Goel and Stroulia 1996, p. 358). *“The specification of a substance includes its properties”* (Goel et al. 2009, p. 24). **Examples** (Goel et al. 2009, p. 31): • Components: gyroscope, worm wheel, pivot • Substance: angular momentum • Connections: contains, connected	1990, p. 182). An entity could be a component, system, or product, its attribute any property which can be observed by scientific means, and a relation any link between entities, attributes, or relations (Umeda et al. 1990). The notion of state implies *“changes of state”* through behaviours “ (Umeda et al. 1990, p. 183). **Examples** (Umeda et al. 1990, p. 182): • Entities: paper weight, paper • Relation: "on", i.e. the paper weight is on the paper. • Attributes of paper weight: weight, volume, density, which are also related to each other.	*they are related”*, i.e. what it is (Qian and Gero 1996, p. 291). *“These structural properties are those which a designer directly manipulates in order to generate a physical solution to an abstract problem. Thus, while designers take many things into consideration in the course of designing, ultimately what they do is select structural variables and assign to them values representing material properties, shape descriptions, dimensions, location and connectivity”* (Rosenman and Gero 1998, p. 169). Elements could be assemblies, components, or parts. *“An element has many properties, or attributes, for example, color, shape, material, and so on. […] If the elements are physical, the relationship between them is a physical interconnection using topological or geometrical data”* (Qian and Gero 1996, p. 292). **Examples** (Gero and Kannengiesser 2004, p. 381**)**: • Elements: glass, frame • Attributes: glazing length, type of coating, type of glass • Relation: glass and frame are geometrically interlinked.

3.3 The ontology of FBS Linkage

Drawing on the detailed comparison of the three seminal FBS ontologies, a new ontology for the FBS Linkage method was developed. The FBS Linkage ontology is composed of eleven assumptions and represented in Table 2~~Table 2~~ using the same scheme as for the above comparison. Contrasting this ontology with the three seminal ontologies discussed above shows that, in general, the FBS Linkage ontology is most closely related to the FBStr ontology as it focuses on product properties rather than on state transitions. However, the FBS Linkage model specifies, enriches, and modifies the FBStr ontology in order to make it more applicable to complex products and usable for change propagation analysis. The specifications comprise a listing and narrowing down of the elements and links of each layer. The enrichments comprise the use and integration of the concepts from Pahl et al. (2007), McMahon (1994), and Hirtz et al. (2002) as means to identify and define these elements and links. The modifications comprise a focus on physical or technical functions described by input/output relations of flows rather than general “verb object” functions which might refer to non-technical functions (e.g. aesthetic functions) and are considered as more subjective. In particular, the reconciled functional basis reported by Hirtz et al. (2002) was adopted for the functional layer, 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 may lead to inconsistencies in a developed model (Eckert et al. 2011).

Table 2: The FBS Linkage ontology

Ontology	FBS Linkage model
Main publi-cations	The FBS Linkage model is based on Gero's FBStr ontology and integrates concepts from: • (Pahl et al. 2007) • (McMahon 1994) • (Hirtz et al. 2002), (Stone and Wood 2000)
Function	**Key distinction**: operations interlinked by flows **Definition:** Function describes what the product is for. It specifies the (1) operations of the product and their (2) interrelations. **1. Functional elements:** Functions can be decomposed from product function to subfunctions at several levels of hierarchy down to a level where they can be linked to the behaviours which realise them (Pahl et al. 2007). They are defined as follows (Stone and Wood 2000, p. 359, 360): "Product function: the general input/output relationship of a product having the purpose of performing an overall task, typically stated in verb-object form. Subfunction: a description of part of a product's overall task (product function), stated in verb-object form. Subfunctions are decomposed from the product function and represent the more elementary tasks of the product." These lowest level functions are termed functional elements. **2. Functional links:** Functional interrelations might exist between functional elements in form of flows of material, energy, and information (Pahl et al. 2007; Rodenacker 1971). **Examples** for the diesel engine (Section 4): • Product function: provide torque. • Subfunctions (i.e. functional elements): import air, transport air to chamber, decrease air temperature. • Functional links: air, fuel, thermal energy etc.
Function - behaviour links	**Key distinction**: rational, subjective (designer's choice), many-to-many relation **3. Rationality of function-behaviour links:** *"Specifically, function is ascribed to behavior by establishing a teleological connection between the human's goals and observable or measurable effects of the object"* (Gero and Kannengiesser 2007, p. 380). The rational links from behavioural attributes to functional elements depend on the designer's goals, experience, and knowledge. Thus, the links from the behavioural layer to the functional layer are rational and subjective. **4. (n:m)-Cardinality of function-behaviour links:** The relation between functional and behavioural elements is of type n:m (i.e. many-to-many). Hence, one functional element may depend on one or many behavioural elements (of different components), and one behavioural element may influence one or many functional elements. **Example** for the diesel engine (Section 4): • The 'convert electrical energy to rotational energy' is linked to the electrical behaviour of the starter motor and the mechanical behaviours of the adapter plate/ flywheel housing and flywheel ring gear.
Beha-viour	**Key distinction:** implicit attributes encompassing physical properties interlinked by product behavioural requirements **Definition:** Behaviour describes what the product does, i.e. how it reacts to external influences due to physical laws. It

Ontology	FBS Linkage model
	specifies (1) behavioural attributes of the constituent artefacts and their (2) behavioural interrelations. **5. Behavioural elements:** Behavioural attributes are *"[…] implicit attributes which describe the characteristics and behaviour of the artefact subjected to the external effects L. The implicit attributes describe the functional performance of the artefact, including such parameters as strength and durability. The term is used here, because the attributes are considered to be implicit in the design of the artefact. They may be estimated from the explicit attributes and the external effects. They may also, in some circumstances, be regarded as relationships between the explicit attributes and the external effects"* (McMahon 1994, p. 198). A behavioural attribute can encompass a group of physical properties, dependent on the type of product and level of detail. As behaviours are the mechanisms by which functions are achieved, these attribute types enable both the functions and the flows between them. Therefore, they are closely related to the types of flows between functions as defined by Hirtz et al. (2002) and Stone and Wood (2000). Behavioural element refers to a behavioural attribute of a specific constituent artefact, e.g. thermal behaviour of the casing. **6. Behavioural links:** Behavioural interrelations might exist between behavioural elements of the same attribute (e.g. thermal behaviour of component 1 and thermal behaviour of component 2) across constituent artefacts of a product due to the product behavioural requirements or proximity of the elements. For example, the product strength depends on the strength of its components or the thermal behaviour of a wire and its coating depend on each other. Ideally, there are no behavioural links between behavioural elements of different attributes (e.g. no link between thermal behaviour and mechanical behaviour). However, this is usually not the case for such behaviours as thermal and electrical. **Examples** for the diesel engine (Section 4): • (High level) behavioural attributes: mechanical (strength, inertia, elasticity, etc.), electrical (conduction, resistance, charging, etc.), thermal (conduction, temperature change, absorption, resistance, etc.). • Behavioural elements: mechanical behaviour of the valve train. • Behavioural links: mechanical behaviour of the valve train is linked to mechanical behaviour of the cylinder head assembly and push rods.
Behaviour-structure (state) links	**Key distinction**: causal, objective (by physical laws), many-to-many relation **7. Causality of links behaviour-structure links:** Behavioural attributes (i.e. implicit attributes) are realised by structural attributes (i.e. explicit attributes) and derivable by means of a physical theory from the structure of the artefact and possibly some properties of the environmental conditions (adapted from Gero (1990) and McMahon (1994)). Thus, the links from the structural layer to the behavioural layer are causal and objective. **8. (n:m)-Cardinality of behaviour-structure links:** The relation between behavioural and structural elements is of type n:m (i.e. many-to-many). Thus, within a component, a behavioural element may depend on one or many structural elements of different structural attributes, and a structural element may influence one or many behavioural elements of different behavioural attributes. **Examples** for the diesel engine (Section 4): • Mechanical behaviour of the valve train is linked to its geometry, material, and surface attributes. • Geometry attribute of the valve train is linked to its mechanical and thermal behaviours.
Structure	**Key distinction:** constituent artefacts, explicit attributes, and relations **Definition:** Structure describes what the product consist of. It specifies what (1) constituent artefacts the design is composed of, what (2) the structural attributes of these artefacts are, and how they are (3) structurally related

Ontology	FBS Linkage model
	(adapted from Qian and Gero (1996)). **9. Structural elements:** Structural attributes are *"[…] explicit attributes describing the design, such as its dimensional parameters, the values of the properties of the materials from which the artefact is constructed, etc. They are termed explicit attributes here, because they must be explicitly defined for the artefact to be made"* (McMahon 1994, p. 198). Structural attributes are grouped into geometry (dimensions, shape descriptions), material (type, volume, density, and other explicit properties of material), surface (surface finish, texture, and micro dimensions of surface), colour (type, tone, intensity, and reflectance), controller (codes, microchips, relays). Structural element refers to a specific structural attribute of a specific constituent artefact, e.g. the material of the casing. **10. Structural links:** Structural interrelations might exist between structural elements of the same attribute (e.g. material of component 1 and material of component 2) across constituent artefacts of a product due to the product structural requirements. For example, the geometry requirement of the product interlinks the geometries of its constituent artefacts. Ideally, there are no structural links between structural elements of different attributes (e.g. no link between material and geometry). **11. Constituent artefacts/ Product decomposition:** A product can be decomposed into its constituent artefacts at different levels of detail. Constituent artefacts may refer to systems, assemblies, components, or parts, dependent on the selected level of detail. **Examples** for the diesel engine (Section 4): • Constituent artefacts (here components): cylinder head assembly, cylinder block assembly, valve train, etc. • Structural attributes: geometry, material, surface, controller. • Structural elements: geometry of the valve train, material of the valve train, etc. • Structural links: geometry of the valve train is linked to geometry of the geometries of the cylinder head assembly, cylinder block assembly, etc.

Assumption 11 is a prerequisite for the FBS Linkage method which models a product's structural and behavioural layers at different levels of decomposition and its functional layer at the product level. The idea of product decomposition into smaller parts is based on a common principle of engineering to break down complex problems into smaller parts that are more easily manageable. Product decomposition is widely accepted and manifested in most other methods (e.g. CPM and other component-based design structure matrices (DSMs)) and strategies (e.g. modular design, product platform based design, and concurrent design).

Assumption 9 is closely linked to the concept of explicit design attributes from McMahon (1994) and elementary design properties from Hubka and Eder (1996). The five structural attributes listed represent generic attributes which are applicable for most artefacts. However, the list might need to be adapted to model specific class of artefacts. Strictly speaking, the structural attributes are not independent; for example, the material of a component might determine its surface finish. However, the dependencies between structural elements of different attributes (e.g. material ↔ geometry) can be neglected compared to the dependencies between structural elements of the same attribute across components (e.g. material of component 1 ↔ material of component 2). The restriction in Assumption 10 is a logical consequence of Assumption 9; the five types of structural elements cannot influence each other in the structural layer because they are considered as (structurally) independent.

Assumption 7 and 8 are drawn from Gero's FBStr model. As the structural layer is linked to the behavioural layer by causality, the links from structural elements to behavioural elements are (causally) deterministic. Thus, a change to a structural element will always have an impact on all behavioural elements which depend on it. On the other hand, due to the *(n:m)*-relation, a change to a behavioural element may be realised by change(s) to different possible structural elements. Thus, the links from behavioural elements backwards to structural elements are "*possibilistic*" and depend on the designer's decisions.

Assumptions 5 and 6, and 1 and 2 are similar to Assumption 9 and 10. Assumptions 3 and 4 are similar to the Assumptions 7 and 8.

3.4 Developing a FBS Linkage scheme

Based on the FBS Linkage ontology described above, a FBS scheme can be developed for the design to be analysed following the five steps depicted in Figure 2.

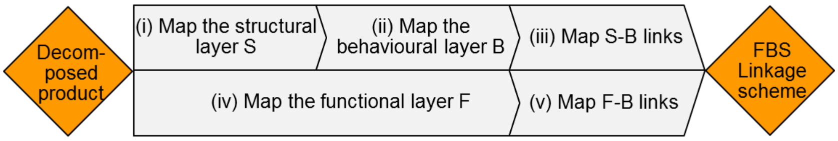


Figure 2: Step-by-step developing of a FBS Linkage scheme

For a given decomposed product, (i) structural and (ii) behavioural attributes can be defined and their elements interlinked to each other within each layer. For the structural layer, a number of ideally-independent attributes such as material, geometry, surface, colour, and controller (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. Then, (iii) the structural elements that determine the component behaviours must be interlinked 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, e.g. 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 from Hirtz et al. (2002). The functional layer does not refer to the selected level of decomposition but to the whole product. 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 interlinked to each other within and between the layers. The characteristic network parts are tagged by the respective ontology assumptions on the right hand side of the figure.

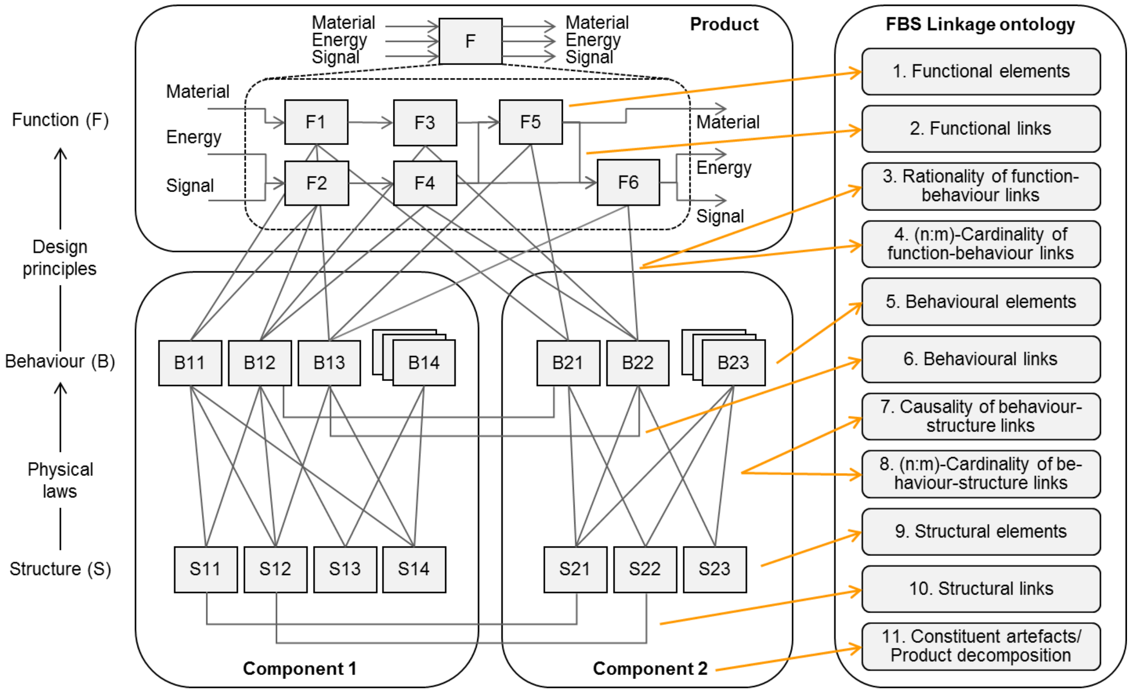


Figure 3: FBS Linkage network and the corresponding ontology assumptions

MDMs are block matrices composed of one DSM for each domain in the diagonal blocks and domain mapping matrices (DMMs) for inter-domain relations off the diagonal blocks. For more background on MDMs, the reader is referred to Lindemann and Maurer (2007); Lindemann et al. (2009); Maurer (2007). In particular, the FBS Linkage MDM is a block tridiagonal matrix composed of a function, a behaviour, and a structure DSM on the main diagonal, and a function-behaviour, a behaviour-function, a behaviour-structure, and a structure-behaviour DMM on the adjacent upper and lower diagonals correspondingly (Figure 4).

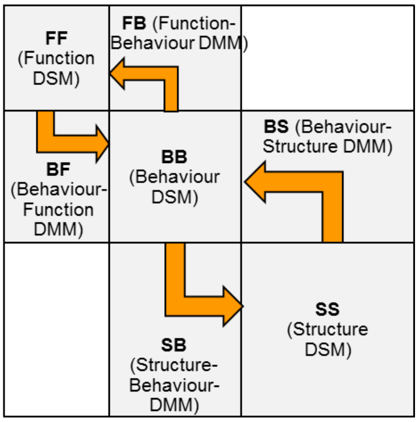


Figure 4: FBS Linkage MDM

The FBS Linkage scheme can be developed at different levels of product decomposition, i.e. for the whole product, or its systems, components, or parts. All three layers may include hierarchical structures breaking down potentially large attributes into a number of smaller attributes as suggested by (Umeda et al. 1990) and (Goel and Bhatta 2004). The higher the degree of decomposition the more information about the product can be stored and the more precisely change propagation can be modelled. All models are consistent (Figure 5); the abstract models (i.e. lower degree of decomposition) can be generated by collapsing the more detailed models; the latter can be generated by detailing the abstract high level models.

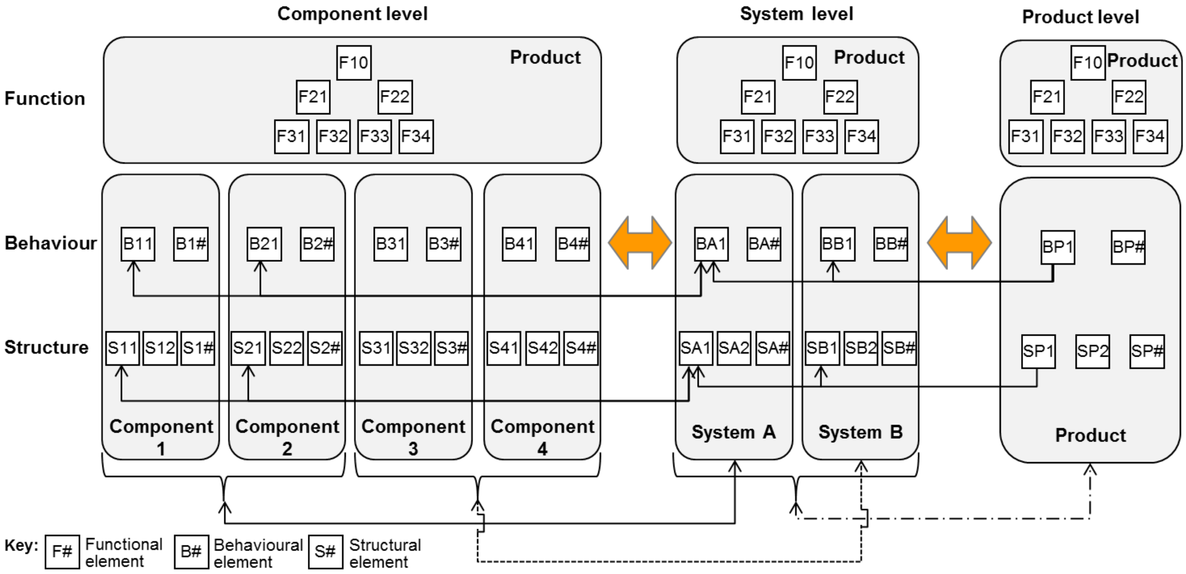


Figure 5: FBS Linkage network for different levels of decomposition

Note: Only selected links are shown to preserve graphical clarity.

The network above is clustered based on components. Alternatively, it can be clustered based on attributes. Accordingly, it can be represented in a component-clustered (Figure 6a) or attribute-clustered MDM (Figure 6b).

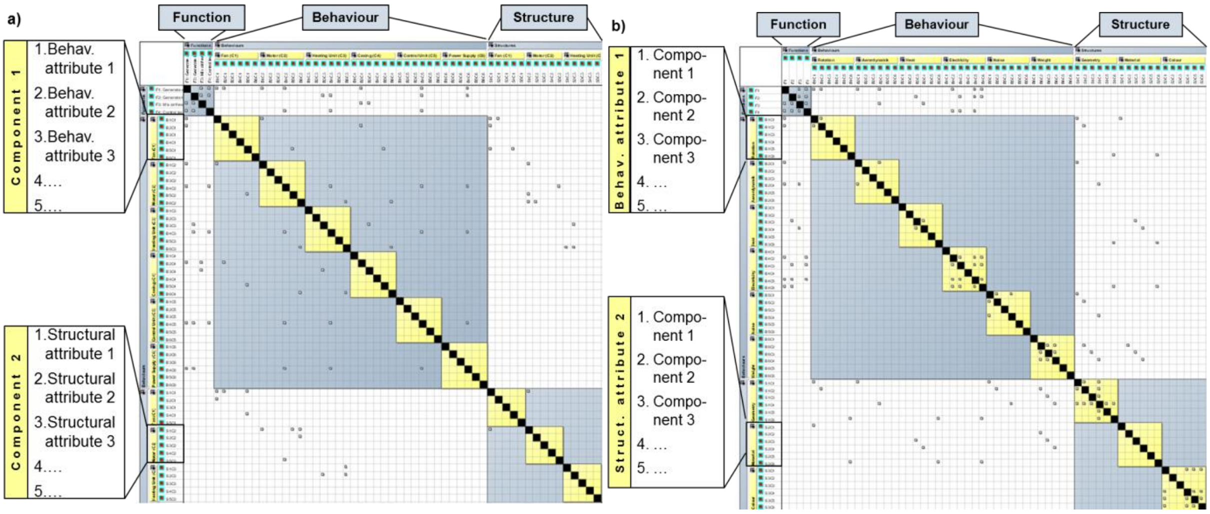


Figure 6: FBS Linkage MDM – (a) component-clustered, (b) attribute-clustered

3.5 FBS Linkage benefits

The FBS Linkage method collects, generates, organises, stores, and represents thorough knowledge about the product. This knowledge can benefit different stakeholders throughout the product lifecycle. As the method combines two established approaches, namely: FR and CPM, it can be applied for purposes targeted by both. FR schemes provide an overall system description which can be applied as a means to support communication and understanding between engineers of various disciplines and facilitate the use of automated reasoning systems (Erden et al. 2008). CPM models provide an overall change description of the system and can be applied during different design stages, amongst others for (Keller et al. 2009; Jarratt et al. 2004b): knowledge capture and familiarisation with existing designs, identifying and predicting change risks, identifying propagation absorbers/ multipliers, testing alternative solutions, team support, and process management.

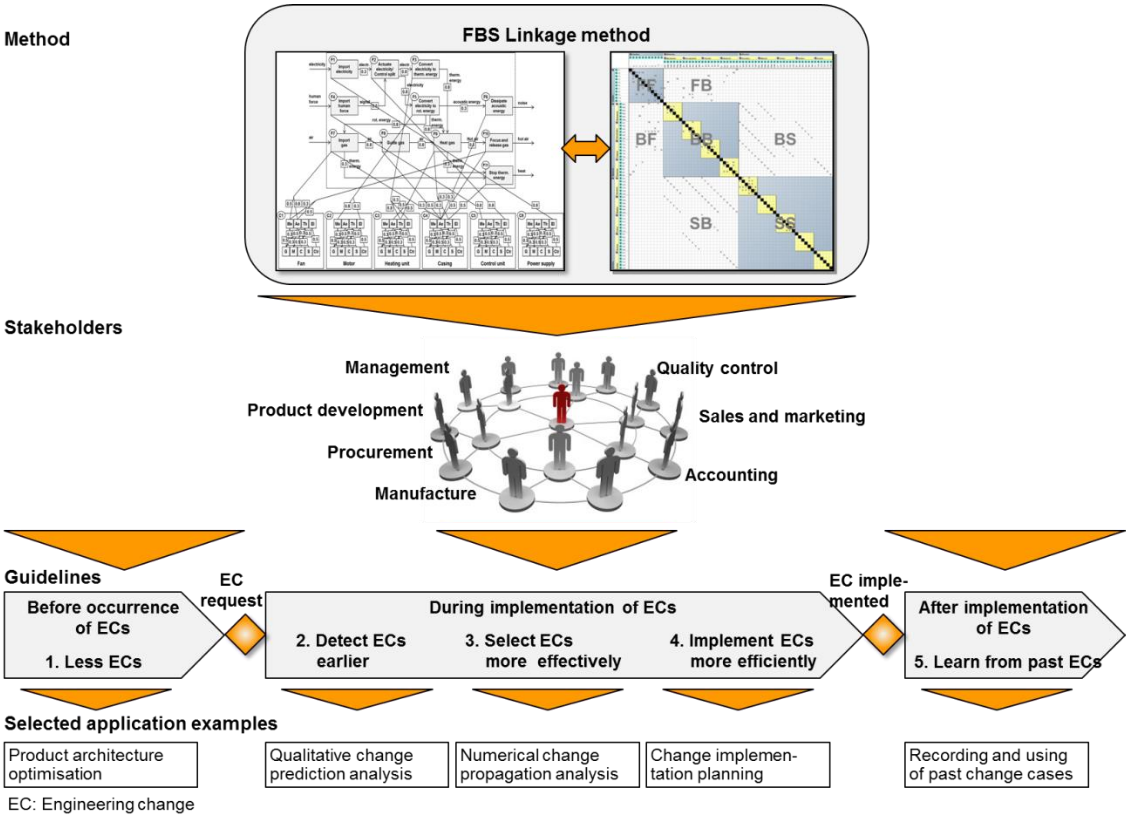


Figure 7: Application of the FBS Linkage method to support EC management

In particular for EC management, the FBS Linkage method can be used to pursue the five guidelines from Fricke et al. (2000) and thus enables a pro-active management of ECs, as illustrated along with selected application examples in Figure 7:

1. To reduce the number of propagated changes, the FBS Linkage model could be used to support optimising the architecture of a design, in such a way that functions are decoupled and critical linkage between structural, behavioural, and functional elements are reduced.
2. To detect ECs earlier and improve communication of propagated changes, the FBS Linkage network could be used to trace possible change propagation paths and predict changes before they actually occur.
3. To select ECs more effectively, the numerical change propagation analysis could be used to prioritise changes which impose low risk to other parts over changes with high risk.
4. To implement EC more efficiently, both the qualitative and quantitative change propagation analysis could be used to select between alternative solutions and develop implementation plans.
5. To learn from the EC history for the future, the FBS Linkage model could be used to record EC cases including their propagation paths and apply the historic data to continuously update and improve the numeric network model.

In contrast to other existing network models of change propagation, particularly the single-layered models, the FBS Linkage network includes all relations between structural, behavioural, and functional elements and therefore avoids “hidden dependencies”. Consequently, two elements cannot influence each other if there is no (direct and/ or indirect) link between them in the FBS Linkage model. Furthermore, the FBS Linkage model allows analysis of the impact of different attributes, components, or functions on the overall change propagation network. For example, it can be calculated how the linkage values change when two functions are decoupled or a specific attribute of a component is frozen. The risk values can be aggregated at different levels of detail to assess change propagation between e.g. components or attributes. When the size of the MDM becomes too huge to be printed on a single page, such aggregated views can help to localise potential risks which can be further analysed by zooming-in gradually. For instance, if the designer wants to change a given attribute, the risk MDM could provide him with a prioritised list of affected components. In a second step, he could then zoom into more detailed views to understand the interdependencies. This would be especially useful for the components of medium significance as the designers are usually aware of impacts on core-components, at one end, and impacts on low significance components can be neglected, at the other end.

Moreover, because the FBS Linkage model makes the product attributes and their relations explicit, it allows direct analysis of all different types of incoming change requests, affecting functions, behaviours, structures or any relations between them. Finally, as the model allows a precise definition of structural elements (e.g. the geometry of a certain component), it provides an interface which can be linked to design tasks of the process domain (e.g. design the geometry of a certain component) to obtain an integrated product-process EC management model.

3.6 FBS Linkage effort

Ideally, if product decompositions and functional reasoning models are already available, they could be used as a modelling aid for the FBS Linkage model and reduce the total modelling effort significantly. However, if the FBS Linkage model has to be developed from scratch, the effort of model building depends mainly on the selected level of decomposition and the complexity and the architecture of the product. The first determines the number of elements (i.e. the size of the network or MDM) and the rest the number of links (i.e. the density of the network or MDM). The matrix structure of the model would normally suggest a quadratic relation between the effort and the number of elements. However, since the MDM in this case is a block tridiagonal matrix, the effort is less than suggested by the total number of its cells because two DMM blocks between structure and function and many other cells inside the other blocks are by definition empty. Furthermore, the generic linking of structural elements to behavioural elements as well as the limited number of structural and behavioural attributes limit the effort of model building.

For the products modelled so far, the effort is in the order of 1 person-day for a hairdryer with six components and in the order of 10 person-days for a diesel engine with 42 components (see Section 4) or a scanning electron microscope (SEM) with 28 components. It is difficult to make any general estimations of the effort required to model other products because the effort depends on the complexity and architecture of the specific product. However, using these numbers above, the following rule of thumb could be deducted for systems up to 42 components: The total FBS Linkage modelling effort in man-hours is between 1 and 2 times the number of components; for products of lower complexity such as the hairdryer, the effort is in the order of 1 person-day; and for products of higher complexity such as the diesel engine, the effort is in the order of 10 person-days.

Once a FBS Linkage scheme has been built, the effort to modify it to model other product variants is significantly less than the initial modelling effort. The vast majority of the components with their structural and behavioural attributes as well as the functions and accordingly the links between structural, behavioural, and functional elements remain similar across product variants. Only a few elements or links need to be changed, added, or dismissed. This is especially useful for platform based product families.

4 FBS Linkage method application to a diesel engine

The inclusion of the FBS Linkage scheme steps (Figure 2) into the method flow diagram (Figure 1) results in the detailed FBS Linkage technique in Figure 8. In the following subsections, this technique is applied to a diesel engine.

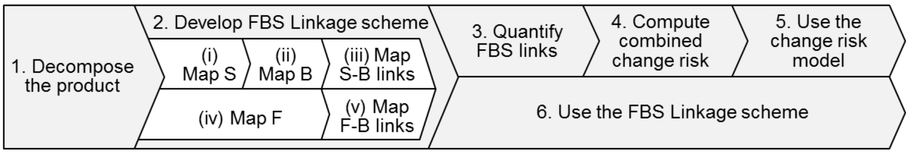
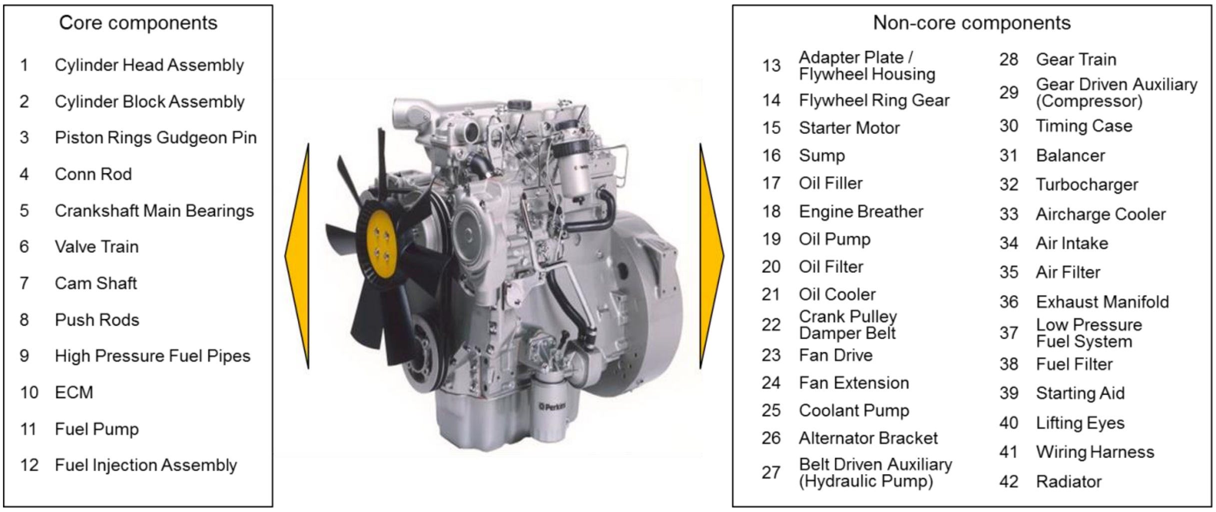


Figure 8: Detailed FBS Linkage technique

4.1 Decompose the product

Dependent on the targeted 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 more in-depth than others. The diesel engine was decomposed into 42 components, 12 of which were considered as core components and received more attention during model building (Figure 9).



Core components

1	Cylinder Head Assembly
2	Cylinder Block Assembly
3	Piston Rings Gudgeon Pin
4	Conn Rod
5	Crankshaft Main Bearings
6	Valve Train
7	Cam Shaft
8	Push Rods
9	High Pressure Fuel Pipes
10	ECM
11	Fuel Pump
12	Fuel Injection Assembly

Non-core components

13	Adapter Plate / Flywheel Housing
14	Flywheel Ring Gear
15	Starter Motor
16	Sump
17	Oil Filler
18	Engine Breather
19	Oil Pump
20	Oil Filter
21	Oil Cooler
22	Crank Pulley Damper Belt
23	Fan Drive
24	Fan Extension
25	Coolant Pump
26	Alternator Bracket
27	Belt Driven Auxiliary (Hydraulic Pump)
28	Gear Train
29	Gear Driven Auxiliary (Compressor)
30	Timing Case
31	Balancer
32	Turbocharger
33	Aircharge Cooler
34	Air Intake
35	Air Filter
36	Exhaust Manifold
37	Low Pressure Fuel System
38	Fuel Filter
39	Starting Aid
40	Lifting Eyes
41	Wiring Harness
42	Radiator

Figure 9: Product decomposition of the diesel engine

Source: Engine photo is used by courtesy of Perkins Engines Company Limited.

4.2 Develop FBS Linkage scheme

(i) Map the structural layer S: The four structural attributes *Geometry (Ge), Material (Ma), Surface (Su)*, and *Controller (Ct)* were used to define 168 structural elements (Figure 10). The colour attribute was left out because it is only of minor significance for the engine design. Although *Controller* is only relevant for a few components, it was kept for all components to preserve consistency in the scheme.

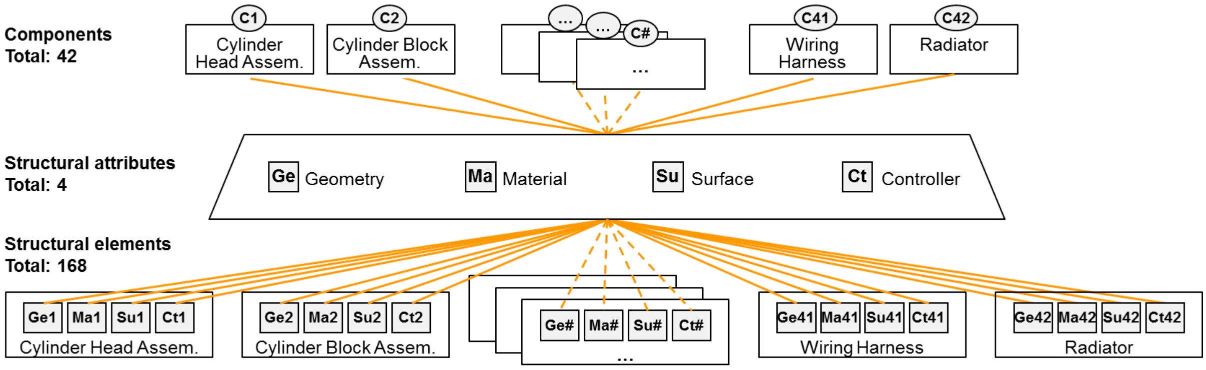


Figure 10: Defining structural elements for the diesel engine

The structural attributes can often be considered independent from each other, i.e. the geometry of a component can be selected independently from its material on a structural level. However, attributes are often related to each other through behaviours and functions, and thus, cannot be determined arbitrarily if behaviours and functions are taken into account. These links can be captured first in separate attribute DSMs, where "x" indicates the existence of a link and then summarised into a larger block matrix. If structural attributes are not independent on the structural level, their interrelations could be captured in the corresponding blocks between the attribute blocks. This would increase the number of dependencies in the model and accordingly the change propagation risk. For the diesel engine, majority of the structural links are symmetric and come from *Geometry* (Figure 11~~Figure 11~~).

ID	Geometry of:	No	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
Ge1	Cylinder Head Assembly	1		x	x			x		x		x	x	x	x										x		x	x	x			x				x		x		x	x			x
Ge2	Cylinder Block Assembly	2	x		x	x	x	x	x	x			x		x			x			x	x	x		x		x			x	x	x	x											x
Ge3	Piston Rings Gudgeon Pin	3	x	x		x	x	x						x																														
Ge4	Conn Rod	4		x	x		x		x																								x											
Ge5	Crankshaft Main Bearings	5		x	x	x										x					x			x						x		x	x											
Ge6	Valve Train	6	x	x	x					x				x																														
Ge7	Cam Shaft	7		x		x																								x														
Ge8	Push Rods	8	x	x				x																																				
Ge9	High Pressure Fuel Pipes	9	x	x								x	x	x									x																x	x	x		x	
Ge10	Electric Control Module	10	x								x		x																		x					x			x				x	
Ge11	Fuel Pump	11	x	x								x																		x		x								x				
Ge12	Fuel Injection Assembly	12	x		x			x																																	x			
Ge13	Adapter Plate / Flywheel Housin	13	x	x												x	x	x																										
Ge14	Flywheel Ring Gear	14					x										x																											
Ge15	Starter Motor	15		x												x						x																						
Ge16	Sump	16		x		x	x								x																	x	x											
Ge17	Oil Filler	17	x									x																				x										x		
Ge18	Engine Breather	18	x	x								x																								x								
Ge19	Oil Pump	19		x			x																							x			x											
Ge20	Oil Filter	20		x													x																							x				
Ge21	Oil Cooler	21	x	x							x	x																																
Ge22	Crank Pulley Damper Belt	22					x																		x				x			x												
Ge23	Fan Drive	23		x																				x		x	x					x												x
Ge24	Fan Extension	24																							x							x												
Ge25	Coolant Pump	25	x	x																					x					x		x												
Ge26	Alternator Bracket	26	x																													x						x						
Ge27	Belt Driven Auxiliary (Hydraulic	27	x										x											x								x												
Ge28	Gear Train	28		x			x		x				x								x						x				x	x	x											
Ge29	Gear Driven Auxiliary (Compress	29		x									x																	x		x							x					
Ge30	Timing Case	30	x	x			x						x					x						x	x	x	x	x	x	x	x													
Ge31	Balancer	31		x		x	x											x			x									x														
Ge32	Turbocharger	32		x																															x			x					x	
Ge33	Aircharge Cooler	33																																x		x								
Ge34	Air Intake	34	x																	x															x									
Ge35	Air Filter	35	x																																									
Ge36	Exhaust Manifold	36	x																															x										
Ge37	Low Pressure Fuel System	37		x							x		x									x									x									x				
Ge38	Fuel Filter	38	x								x	x										x																						
Ge39	Starting Aid	39	x								x			x																													x	
Ge40	Lifting Eyes	40	x																x																									
Ge41	Wiring Harness	41										x					x											x						x							x			
Ge42	Radiator	42	x	x																					x																			

Figure 11: Geometry attribute DSM for the diesel engine

(i) Map the behavioural layer B: Similarly to the structural elements, 126 behavioural elements were defined using the three behavioural attributes: *Mechanical (Me)*, *Electrical (El)*, and *Thermal (Th)* (Figure 12). Again, the *Electrical* behaviour of many components is not relevant and their corresponding elements could be left out but were kept for consistency reasons.

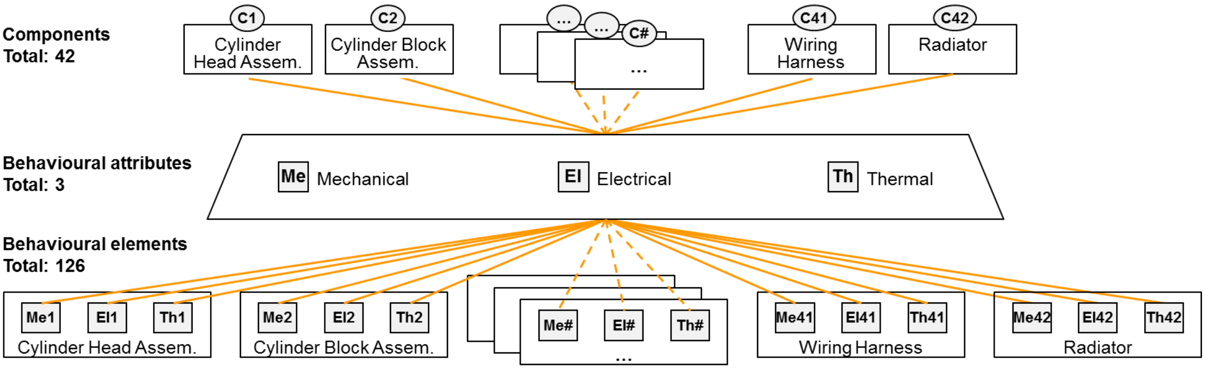


Figure 12: Defining behavioural elements for the diesel engine

The behavioural links between these 126 elements were first captured in behavioural attribute DSMs and then put together into a behaviour DSM. The *Mechanical* behaviour DSM represented in Figure 13~~Figure 13~~ is the densest attribute DSM.

ID	Mechanical behaviour of:	No	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
Me1	Cylinder Head Assembly	1		x	x			x						x																														
Me2	Cylinder Block Assembly	2	x		x		x		x				x																	x			x											
Me3	Piston Rings Gudgeon Pin	3	x	x		x																																						
Me4	Conn Rod	4			x		x																																					
Me5	Crankshaft Main Bearings	5		x		x										x								x						x														
Me6	Valve Train	6	x							x																																		
Me7	Cam Shaft	7		x						x																				x														
Me8	Push Rods	8						x	x																																			
Me9	High Pressure Fuel Pipes	9											x	x																														
Me10	Electric Control Module	10	x																																									
Me11	Fuel Pump	11		x										x																x		x												
Me12	Fuel Injection Assembly	12	x										x																															
Me13	Adapter Plate / Flywheel Housin	13		x																																								
Me14	Flywheel Ring Gear	14					x										x																											
Me15	Starter Motor	15		x																																								
Me16	Sump	16		x																																								
Me17	Oil Filler	17																																										
Me18	Engine Breather	18																																										
Me19	Oil Pump	19					x																																					
Me20	Oil Filter	20		x																																								
Me21	Oil Cooler	21																																										
Me22	Crank Pulley Damper Belt	22					x																						x															
Me23	Fan Drive	23																						x																				
Me24	Fan Extension	24																																										
Me25	Coolant Pump	25																																										
Me26	Alternator Bracket	26																																										
Me27	Belt Driven Auxiliary (Hydraulic	27																						x																				
Me28	Gear Train	28		x			x		x				x																		x		x											
Me29	Gear Driven Auxiliary (Compress	29																												x														
Me30	Timing Case	30		x			x						x																x		x													
Me31	Balancer	31		x	x	x	x																							x														
Me32	Turbocharger	32																																										
Me33	Aircharge Cooler	33																																										
Me34	Air Intake	34																																										
Me35	Air Filter	35																																										
Me36	Exhaust Manifold	36	x																																									
Me37	Low Pressure Fuel System	37											x																															
Me38	Fuel Filter	38											x																															
Me39	Starting Aid	39																																										
Me40	Lifting Eyes	40																																										
Me41	Wiring Harness	41																																										
Me42	Radiator	42																																										

Figure 13: Mechanical attribute DSM for the diesel engine

(iii) Map the structure-behaviour (S-B) links: The links between structural and behavioural attributes are determined by physical laws, and thus, for the most part independent from the components. For instance, Electrical behaviour depends on the Material and Controller attributes but not on Geometry or Surface attributes. The strength of the links (i.e. likelihood and impact of change propagation), on the other hand, may differ according to the components.

The links between the structural and behavioural elements were identified collectively and symmetrically for all corresponding elements using the attribute relations depicted in Figure 14. If the attribute link was not relevant on the element level, it was removed subsequently.

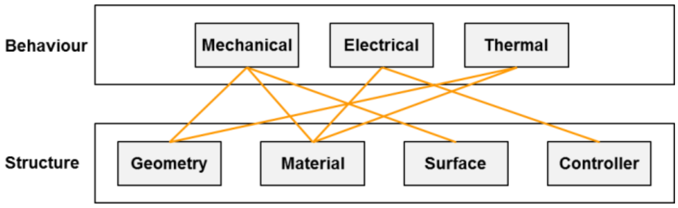


Figure 14: Defining the links between the structural and behavioural attributes of the diesel engine

(iv) Map the functional layer F: The functional layer of products can be modelled using the reconciled functional basis suggested by Hirtz et al. (2002). For the diesel engine, 40 subfunctions were identified and linked to each other by flows of material, energy, and signal (Figure 15). 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.

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 and in other cases less precise. For example, on one hand, while Hirtz et al. (2002) use 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 *"(F1) Start engine"* 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.

A key characteristic of the functional model of the diesel engine is its cycles. This is represented by the up and down movement of the piston as a material flow through the functions F9, F14, F27, and F35.

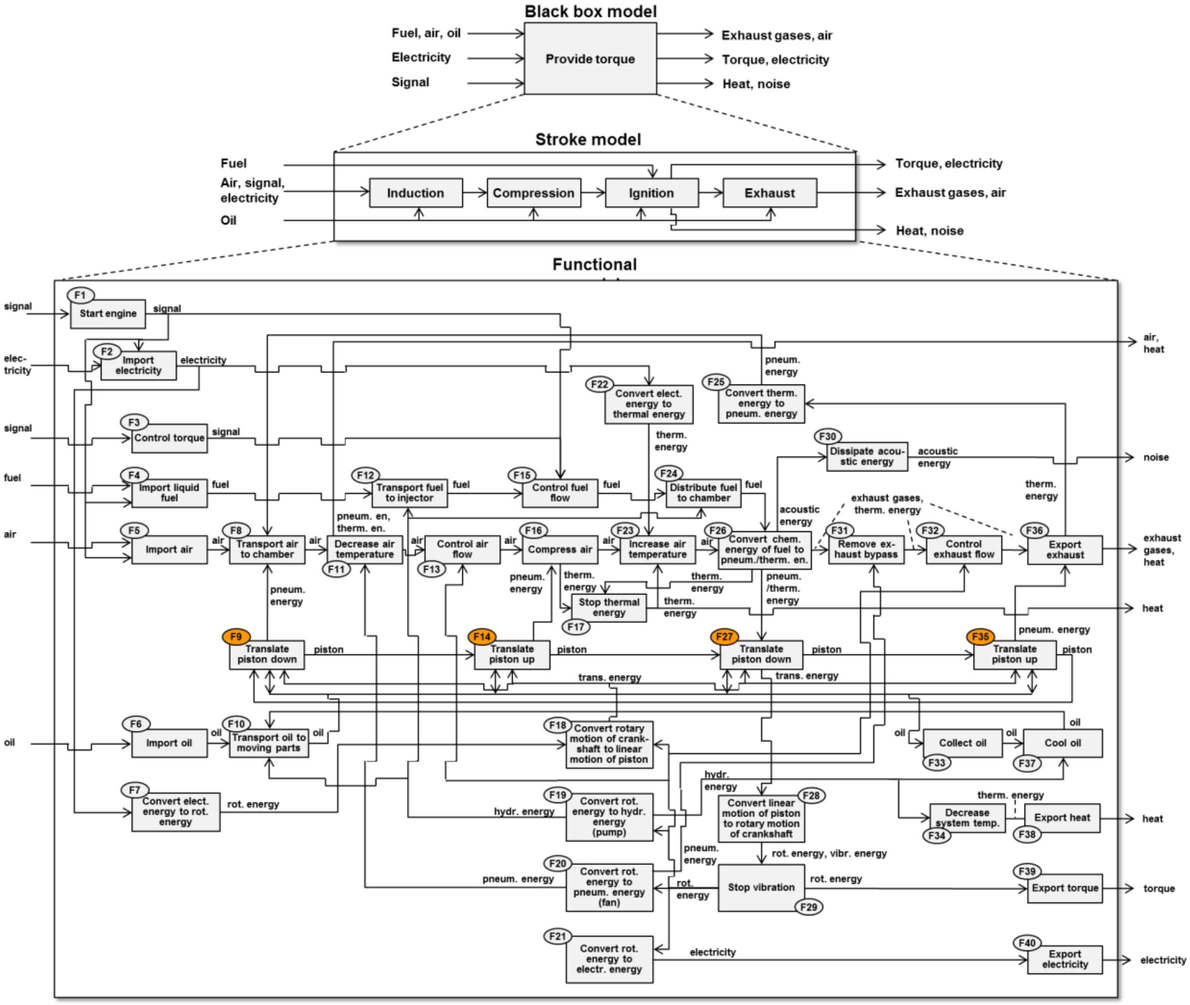


Figure 15: Functional elements and links of the diesel engine

Although the functional block diagram in Figure 15 is directed to indicate the flows, for change propagation and thus within the FBS Linkage model, it was 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 chemical energy of fuel to pneumatic/thermal energy’ (F26) with the aim to increase the torque might impact not only its successor function ‘Remove exhaust bypass’ (F31) – because possibly more exhaust would be produced – but also its predecessor function ‘Distribute fuel to chamber (F24) – because more fuel would likely be required. Consequently, the functional layer DSM is symmetric (Figure 16).

ID	Function name	No	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
F1	Start engine	1		x		x	x										x																									
F2	Import electricity	2	x						x															x																		
F3	Control torque	3															x																									
F4	Import liquid fuel	4	x											x																												
F5	Import air	5	x							x																																
F6	Import oil	6										x																														
F7	Convert elect. energy to rot. ene	7		x																x																						
F8	Transport air to chamber	8					x				x		x														x															
F9	Translate piston down	9								x		x				x				x															x		x					
F10	Transport oil to moving parts	10						x			x					x					x								x								x		x			
F11	Decrease air temparature	11								x					x							x																				
F12	Transport fuel to injector	12				x											x				x																					
F13	Control air flow	13											x					x													x											
F14	Translate piston up	14									x	x						x		x									x						x							
F15	Control fuel flow	15	x		x									x												x																
F16	Compress air	16													x	x			x						x																	
F17	Stop therm. energy	17																x							x			x														
F18	Convert rotary motion of cranksh	18							x		x					x													x		x						x					
F19	Convert rot. energy to hydr. ener	19										x		x												x					x					x			x			
F20	Convert rot. energy to pneum. e	20											x																		x		x									
F21	Convert rot. energy to electr. Ene	21																													x											x
F22	Convert elect. energy to therm. e	22		x																					x																	
F23	Increase air temparature	23																x	x					x				x														
F24	Distribute fuel to chamber	24															x				x							x														
F25	Convert therm. energy to pneum	25								x																												x				
F26	Convert chem. energy of fuel to	26																	x						x	x			x			x	x									
F27	Translate piston down	27										x				x				x								x		x					x		x					
F28	Convert linear motion of piston t	28																											x		x											
F29	Stop vibration	29													x					x	x	x	x							x				x							x	
F30	Dissipate acoustic energy	30																										x														
F31	Remove exhaust bypass	31																				x						x						x								
F32	Control exhaust flow	32																													x		x					x				
F33	Collect oil	33									x					x													x								x		x			
F34	Decrease system temperature	34																			x																			x		
F35	Translate piston up	35									x	x								x									x						x			x				
F36	Export exhaust	36																									x							x			x					
F37	Cool oil	37										x									x														x							
F38	Export Heat	38																																		x						
F39	Export torque	39																													x											
F40	Export electricity	40																					x																			

Figure 16: functional layer DSM for the diesel engine

(v) Map the function-behaviour (F-B) links: In order to develop the links between functional and behavioural elements, first the links from functional elements to components were identified. Then, these links were specified into undirected functional element - behavioural element links as shown in Table 3.

Table 3: Mapping of the function-behaviour links of the diesel engine

No	Subfunction	No of component for:		
		Thermal behaviour	Electrical behaviour	Mechanical behaviour
1	Start engine		10,41	
2	Import electricity		41	
3	Control torque		10,41	
4	Import liquid fuel			37,38
5	Import air			34,35
6	Import oil			17
7	Convert elect. energy to rot. energy		15	13,14
8	Transport air to chamber	32,34		32,34
9	Translate piston down			1,2,3,4,5
10	Transport oil to moving parts			19,20
11	Decrease air temperature	33		
12	Transport fuel to injector	9		9
13	Control air flow		10,41	6,7,8,22,28,30
14	Translate piston up	1,2,3		1,2,3,4,5
15	Control fuel flow		10,41	6,7,22,28,30
16	Compress air	1,2,3,8		1,2,3,8
17	Stop therm. energy	1,2,3,8		
18	Convert rotary motion of crankshaft to linear motion of piston			3,4,5

No	Component
1	Cylinder Head Assembly
2	Cylinder Block Assembly
3	Piston Rings Gudgeon Pin
4	Conn Rod
5	Crankshaft Main Bearings
6	Valve train
7	Cam Shaft
8	Push rods
9	High Pressure Fuel Pipes
10	Electric Control Module
11	Fuel Pump
12	Fuel Injection Assembly
13	Adapter Plate / Flywheel Housing
14	Flywheel Ring Gear
15	Starter Motor
16	Sump
17	Oil Filler
18	Engine Breather

No	Subfunction	No of component for:		
		Thermal behaviour	Electrical behaviour	Mechanical behaviour
19	Convert rot. energy to hydr. energy			19,22,25,27,30
20	Convert rot. energy to pneum. energy			22,23,24,29,30
21	Convert rot. energy to electr. Energy		26	22,26,30
22	Convert elect. energy to therm. energy		39	
23	Increase air temperature	1,2,3		
24	Distribute fuel to chamber		12	12
25	Convert therm. energy to pneum. energy	32		32
26	Convert chem. energy of fuel to pneum./ therm. energy	1,2,3		1,2,3
27	Translate piston down	1,2,3		1,2,3,4,5
28	Convert linear motion of piston to rotary motion of crankshaft			3,4,5
29	Stop vibration			30, 31
30	Dissipate acoustic energy			1,2
31	Remove exhaust bypass	18		18
32	Control exhaust flow	8	10	6,7,8,22,28,30
33	Collect oil	16		16
34	Decrease system temperature	25		25
35	Translate piston up	1,2,3		1,2,3,4,5
36	Export exhaust	32,36		32,36
37	Cool oil	21		21
38	Export Heat	42		42
39	Export torque			13,14,28
40	Export electricity		41	

No	Component
19	Oil Pump
20	Oil Filter
21	Oil Cooler
22	Crank Pulley Damper Belt
23	Fan Drive
24	Fan Extension
25	Coolant Pump
26	Alternator Bracket
27	Belt Driven Auxiliary (hydraulic pump)
28	Gear Train
29	Gear Driven Auxiliary (compressor)
30	Timing Case
31	Balancer
32	Turbocharger
33	Aircharge Cooler
34	Air Intake
35	Air Filter
36	Exhaust Manifold
37	Low Pressure Fuel System
38	Fuel Filter
39	Starting Aid
40	Lifting Eyes
41	Wiring Harness
42	Radiator

Finally, all links and elements were put together to complete the FBS Linkage scheme for the diesel engine.

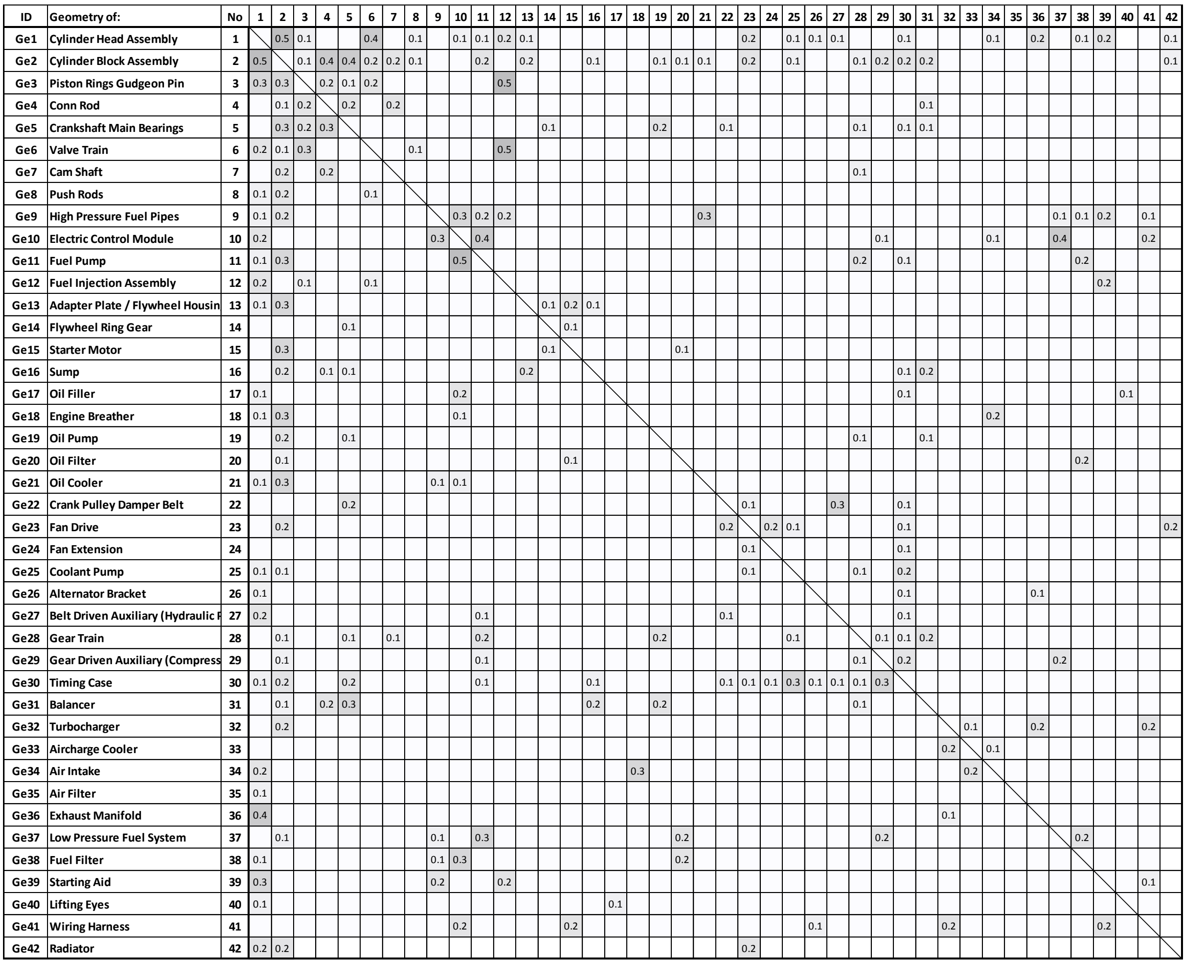
4.3 Quantify FBS links

The direct FBS links can be quantified by likelihood and impact of change propagation. Both values can be estimated gradually between 0 and 1, where 0 indicates no likelihood or impact and 1 indicates certain change propagation or full impact. While the traditional CPM approach captures the links only on a component level subsuming all types of interactions between their attributes (i.e. structural, behavioural, and functional), 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. For instance, there must be a link between the elements *Material* and *Thermal behaviour* of a given component. 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, the obtained values can replace the estimations to improve the model's accuracy. An algorithm to achieve this is discussed in (Hamraz et al. 2013b). However, maintaining the probabilistic character of CPM is recommended - the probabilistic approach reduces the complexity and effort of model building, because estimated linkage values are easier to obtain than deterministic calculations.

In general, each link between two elements could be quantified individually and separately for each direction. This would require each cell which contains a "x" in the FBS Linkage MDM to be quantified separately. 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, (3) some other links can be quantified by standard values if they have not been specified yet, e.g. 0.5 for likelihood and 0.3 for impact, and (4) the remaining links could be quantified using a different grades between 0 and 1, e.g. 0.10 for very low, 0.25 for low, 0.50 for medium, and 0.75 for high, and 0.90 for very 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. For the diesel engine for instance, if the diameter of the Cylinder Block Assembly (C2) is increased, it will require the Cylinder Head Assembly (C1) diameter to be increased accordingly to house the bigger block, whereas a decrease of the same diameter is less likely to propagate to the Cylinder Head Assembly. Assuming that 50% of the generic change cases require an increase and 50% a decrease of the Piston diameter, it can be concluded that the likelihood of change propagation from the Geometry attribute of the Cylinder Block Assembly (Ge2) to the Geometry attribute of the Cylinder Head Assembly (Ge1) is 0.5. The impact of change propagation for this link is very low (0.1) as in case of actual propagation, not the whole Cylinder Head Assembly has to be re-designed but only the corresponding diameter.

The intralayer links between structural and behavioural elements were quantified drawing on the linkage types and values defined in the CPM model from Jarratt et al. (2004a). The quantified DSM for the attribute Geometry is represented in Figure 17.



ID	Geometry of:	No	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
Ge1	Cylinder Head Assembly	1		0.5	0.1			0.4		0.1		0.1	0.1	0.2	0.1										0.2		0.1	0.1	0.1			0.1				0.1		0.2		0.1	0.2			0.1
Ge2	Cylinder Block Assembly	2	0.5		0.1	0.4	0.4	0.2	0.2	0.1			0.2		0.2			0.1			0.1	0.1	0.1		0.2		0.1			0.1	0.2	0.2	0.2											0.1
Ge3	Piston Rings Gudgeon Pin	3	0.3	0.3		0.2	0.1	0.2						0.5																														
Ge4	Conn Rod	4		0.1	0.2		0.2		0.2																								0.1											
Ge5	Crankshaft Main Bearings	5		0.3	0.2	0.3										0.1					0.2			0.1						0.1		0.1	0.1											
Ge6	Valve Train	6	0.2	0.1	0.3					0.1				0.5																														
Ge7	Cam Shaft	7		0.2		0.2																								0.1														
Ge8	Push Rods	8	0.1	0.2				0.1																																				
Ge9	High Pressure Fuel Pipes	9	0.1	0.2								0.3	0.2	0.2									0.3																0.1	0.1	0.2		0.1	
Ge10	Electric Control Module	10	0.2								0.3		0.4																		0.1					0.1			0.4				0.2	
Ge11	Fuel Pump	11	0.1	0.3								0.5																		0.2		0.1								0.2				
Ge12	Fuel Injection Assembly	12	0.2		0.1			0.1																																	0.2			
Ge13	Adapter Plate / Flywheel Housin	13	0.1	0.3												0.1	0.2	0.1																										
Ge14	Flywheel Ring Gear	14					0.1										0.1																											
Ge15	Starter Motor	15		0.3												0.1						0.1																						
Ge16	Sump	16		0.2		0.1	0.1								0.2																	0.1	0.2											
Ge17	Oil Filler	17	0.1									0.2																				0.1										0.1		
Ge18	Engine Breather	18	0.1	0.3								0.1																								0.2								
Ge19	Oil Pump	19		0.2			0.1																							0.1			0.1											
Ge20	Oil Filter	20		0.1													0.1																							0.2				
Ge21	Oil Cooler	21	0.1	0.3							0.1	0.1																																
Ge22	Crank Pulley Damper Belt	22					0.2																		0.1				0.3			0.1												
Ge23	Fan Drive	23		0.2																				0.2		0.2	0.1					0.1												0.2
Ge24	Fan Extension	24																							0.1							0.1												
Ge25	Coolant Pump	25	0.1	0.1																					0.1					0.1		0.2												
Ge26	Alternator Bracket	26	0.1																													0.1						0.1						
Ge27	Belt Driven Auxiliary (Hydraulic	27	0.2										0.1											0.1								0.1												
Ge28	Gear Train	28		0.1			0.1		0.1				0.2								0.2						0.1				0.1	0.1	0.2											
Ge29	Gear Driven Auxiliary (Compress	29		0.1									0.1																	0.1		0.2							0.2					
Ge30	Timing Case	30	0.1	0.2			0.2						0.1					0.1						0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.3													
Ge31	Balancer	31		0.1		0.2	0.3											0.2			0.2									0.1														
Ge32	Turbocharger	32		0.2																															0.1			0.2					0.2	
Ge33	Aircharge Cooler	33																																0.2		0.1								
Ge34	Air Intake	34	0.2																	0.3															0.2									
Ge35	Air Filter	35	0.1																																									
Ge36	Exhaust Manifold	36	0.4																															0.1										
Ge37	Low Pressure Fuel System	37		0.1							0.1		0.3									0.2									0.2									0.2				
Ge38	Fuel Filter	38	0.1								0.1	0.3										0.2																						
Ge39	Starting Aid	39	0.3								0.2			0.2																													0.1	
Ge40	Lifting Eyes	40	0.1																0.1																									
Ge41	Wiring Harness	41										0.2					0.2											0.1						0.2							0.2			
Ge42	Radiator	42	0.2	0.2																					0.2																			

Figure 17: Geometry attribute DSM including change likelihood values for the diesel engine

The links between functional elements were quantified under the symmetry assumption using a change impact value of 0.1 for all links and one of the three different values for change likelihood, namely: 0.3 for low, 0.5 for medium, and 0.8 for high as represented in Figure 18. All interlayer links were defined using 0.5 for change likelihood and 0.1 for change impact.

ID	Function name	No	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
F1	Start engine	1		0.3		0.3	0.3										0.3																									
F2	Import electricity	2	0.3						0.3															0.3																		
F3	Control torque	3															0.3																									
F4	Import liquid fuel	4	0.3											0.3																												
F5	Import air	5	0.3							0.3																																
F6	Import oil	6										0.3																														
F7	Convert elect. energy to rot. ene	7		0.3																0.3																						
F8	Transport air to chamber	8					0.3				0.3		0.3														0.3															
F9	Translate piston down	9								0.3		0.3				0.5				0.5															0.3		0.5					
F10	Transport oil to moving parts	10						0.3			0.3					0.3					0.3								0.3								0.3		0.3			
F11	Decrease air temparature	11								0.3					0.3							0.3																				
F12	Transport fuel to injector	12				0.3											0.3				0.3																					
F13	Control air flow	13											0.3					0.3													0.3											
F14	Translate piston up	14									0.5	0.3						0.5		0.5									0.5						0.3							
F15	Control fuel flow	15	0.3		0.3									0.3												0.3																
F16	Compress air	16													0.3	0.5			0.5						0.5																	
F17	Stop therm. energy	17																0.5							0.3			0.5														
F18	Convert rotary motion of cranksh	18							0.3		0.5					0.5													0.5		0.3						0.5					
F19	Convert rot. energy to hydr. ener	19										0.3		0.3												0.3					0.3					0.3			0.3			
F20	Convert rot. energy to pneum. e	20											0.3																		0.3		0.3									
F21	Convert rot. energy to electr. Ene	21																													0.3											0.3
F22	Convert elect. energy to therm.	22		0.3																					0.3																	
F23	Increase air temparature	23																0.5	0.3					0.3				0.8														
F24	Distribute fuel to chamber	24															0.3				0.3							0.8														
F25	Convert therm. energy to pneum	25								0.3																												0.3				
F26	Convert chem. energy of fuel to	26																	0.5						0.8	0.8			0.8			0.3	0.3									
F27	Translate piston down	27										0.3				0.5				0.5								0.8		0.8					0.3		0.5					
F28	Convert linear motion of piston	28																											0.8		0.3											
F29	Stop vibration	29													0.3					0.3	0.3	0.3	0.3							0.3				0.3							0.3	
F30	Dissipate acoustic energy	30																										0.3														
F31	Remove exhaust bypass	31																				0.3						0.3						0.3								
F32	Control exhaust flow	32																													0.3		0.3					0.3				
F33	Collect oil	33									0.3					0.3													0.3								0.3		0.3			
F34	Decrease system temperature	34																			0.3																			0.3		
F35	Translate piston up	35									0.5	0.3								0.5									0.5						0.3			0.3				
F36	Export exhaust	36																									0.3							0.3			0.3					
F37	Cool oil	37										0.3									0.3														0.3							
F38	Export Heat	38																																		0.3						
F39	Export torque	39																													0.3											
F40	Export electricity	40																					0.3																			

Figure 18: Function DSM including likelihood values of change propagation for the diesel engine

4.4 Compute combined change risk

The Forward CPM algorithm can be applied to the numerical FBS Linkage scheme including direct likelihood and impact values of change propagation to calculate a combined risk matrix. So far, the Forward CPM algorithm has been discussed only in the context of single-domain networks, i.e. DSMs (Keller 2007). As all elements in a FBS scheme are equal in terms of receiving and forwarding changes, this multi-layer network obeys the same rules as a single-layer network. Thus, the Forward CPM algorithm can be applied to the MDM in the same way. However, as the FBS network consists of three layers which are connected in series, at least four steps of change propagation are required to consider indirect change propagation between two structural or two 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 (e.g. C1→C2→C3). Therefore, five or six steps of change propagation should be considered for the FBS Linkage model, two steps more than suggested for CPM (Clarkson et al. 2004).

The likelihood and the impact FBS Linkage MDMs were transferred into CAM, where the Forward CPM algorithm was applied to them to calculate the combined change risks considering six steps of propagation. The detailed results are represented in the risk MDM in Figure 19. 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.

This MDM includes risk values for all different element pairs. It can be collapsed or aggregated in different ways to generate specific high level views of change propagation. For example, the blocks within the structural and behavioural layers can be aggregated to generate a component-component change risk plot, similar to the result of CPM (see e.g. Keller et al. 2009). While the MDM incorporates the detailed FBS information useful for tracing specific change paths, these collapsed views provide a high-level overview. For instance, the component-component DSM indicates the overall propensity of each component to receive or transmit change. When aggregating risk values, different operations (e.g. arithmetic average, arithmetic sum, intersection, maximum, etc.) could be applied (for a discussion, see Simons 2000). However, from a risk management perspective, the maximum operation (i.e. $\max_{(i,j)\in z}(a_{ij})$ for a defined matrix range z), makes sense because it reflects the worst case scenario which a risk manager often has to control.

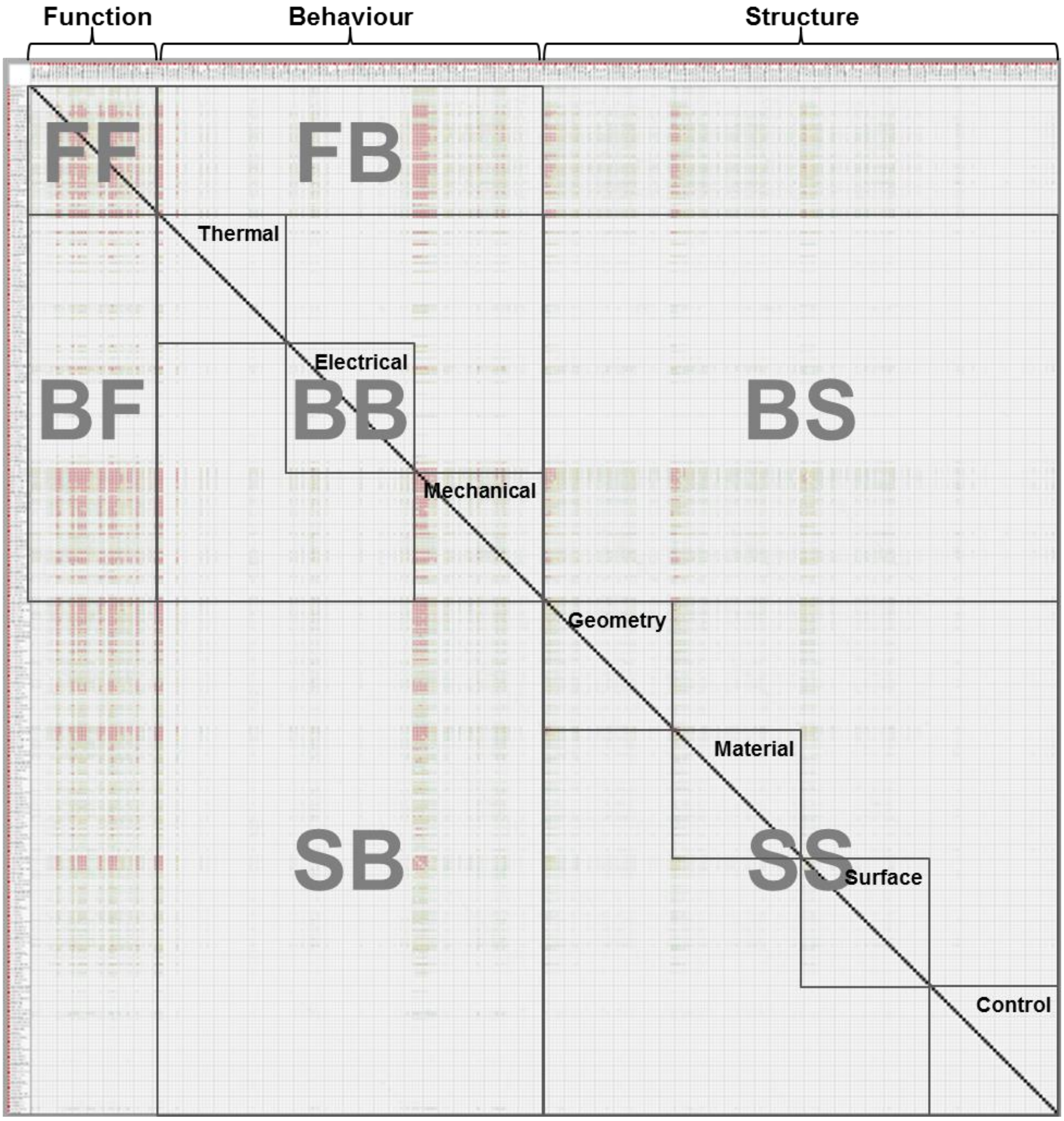
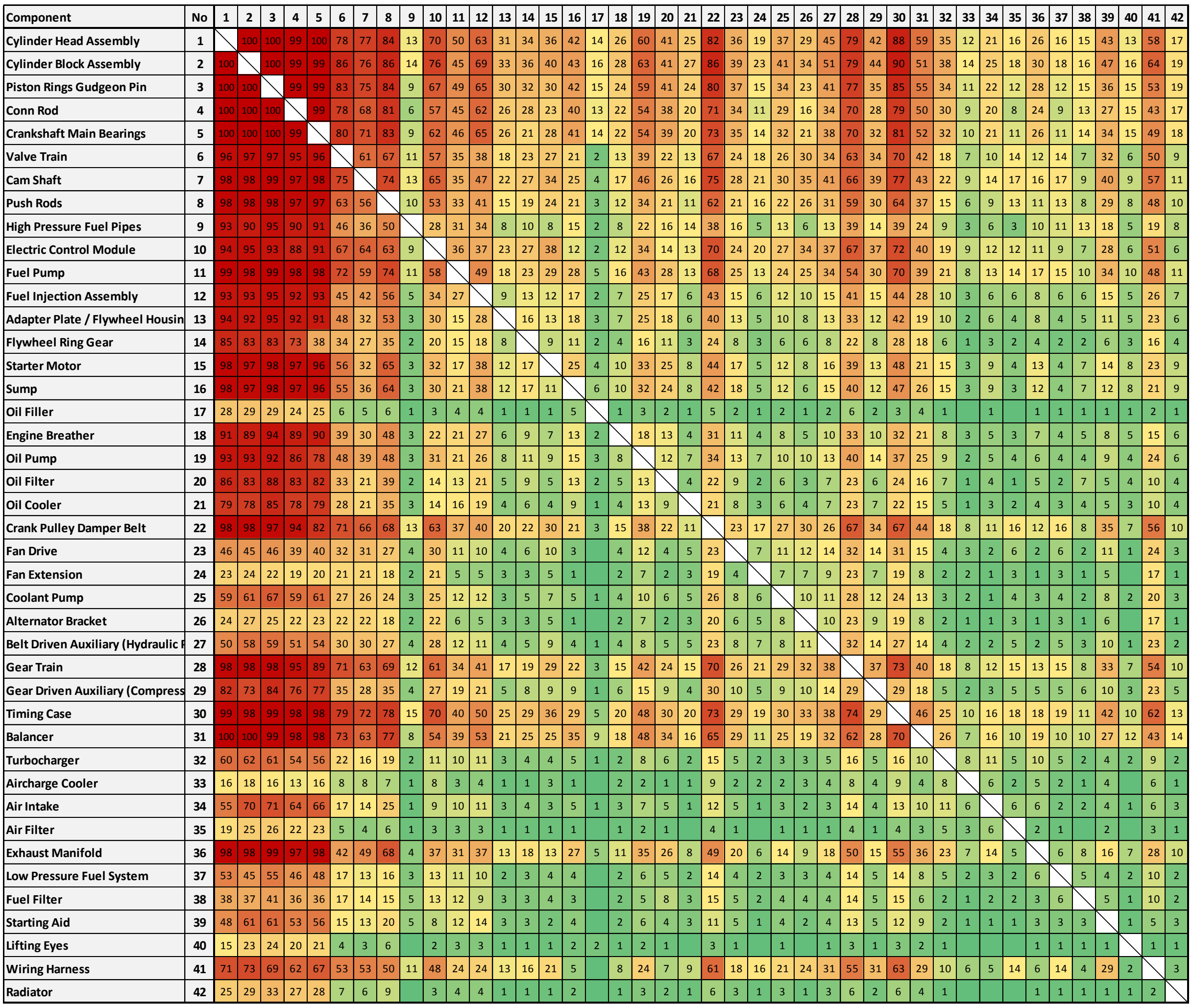


Figure 19: Combined risk MDM for the diesel engine

4.5 Use the change risk model

The combined risk MDM in Figure 19 shows the dependencies between the functional, behavioural, and structural layers in multiple attribute dimensions. It is more populated than the direct likelihood or impact MDMs and has only a few empty cells.

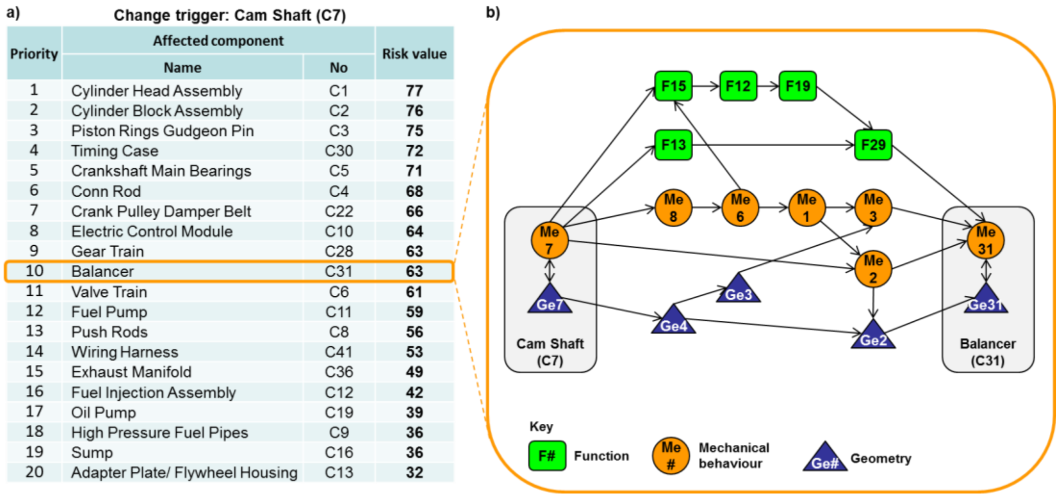
A comparison of the DSMs along the diagonal of this MDM shows that the function DSM (FF) has the highest density. This means that the functions are highly integrated and interdependent. This is expected and can be explained because most functions are part of one of the four diesel engine strokes. A change to one function impacts the corresponding stroke, which in turn is most likely to impact the other strokes. For instance, an increase of the induction volume would affect the compression, ignition, and exhaust strokes. The second densest DSM is the mechanical behaviour DSM. This suggests that the components' mechanical behaviours are highly interdependent. This is reasonable because the diesel engine works mainly mechanically, and thus, the mechanical stress of its components is high. Consequently, changes affecting mechanical behaviours of one component impose high risk to other components. In a more detailed model, the mechanical behaviours could be further subdivided into static load, dynamic load, aerodynamic behaviour, etc. to investigate these relations more rigorously.



Component	No	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	81	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	81	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		49	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	91	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	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	

Figure 20: Aggregated combined risk DSM for the diesel engine

For high level analyses, the behavioural and structural layers of the combined risk MDM were aggregated using the maximum operation to obtain the component-component risk DSM in Figure 20. This DSM includes the maximum combined risk values of the three behavioural and four structural attribute DSMs as well as the 24 square DMMs between them. The high 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 to one component may affect almost any other component. The density distribution represented by the colours (i.e. red for high risk, yellow for medium risk, and green for low risk) indicates that the core components (C1 to C12) are more critical towards receiving changes from other components (i.e. rows 1 to 12) as well as imposing changes to other components (i.e. columns 1 to 12), and especially among each other (cells within rows and columns 1 to 12). Such a DSM helps identify risk absorbers and multipliers (Eckert et al. 2004) and compare the component risk profiles to each other (Keller et al. 2009). As this DSM was generated using the maximum operator for aggregation, it shows the worst case scenario of change propagation; the DSM does not differentiate between the types of change (e.g. Geometry, Material, Electrical behaviour) and assumes that all component attributes are affected simultaneously while taking the highest risk into account. However, this DSM 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.


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 21: a) Prioritised change risk list for Cam Shaft and b) selected change propagation paths from Cam Shaft to Balancer

For instance, Figure 21a 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 21b 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.

4.6 Use the FBS Linkage scheme

The FBS Linkage scheme shows how the product's structure is organised to exhibit actual behaviours which realise its functions. This scheme can be used to investigate potential propagation paths of changes, develop and test alternative solutions, and develop strategies for change propagation containment. For instance, when a function has to be changed, the FBS network shows different behaviours which realise this function and accordingly the structural elements which exhibit those behaviours. The network helps to identify the elements and supports finding solutions. At the same time, it can be used to investigate which elements to manipulate to accommodate the functional change most effectively. These applications support a more pro-active management of ECs.

5 Evaluation

In the Design Research Methodology (DRM), Blessing and Chakrabarti (2009) differentiate between three kinds of evaluation:

1. *Support evaluation* involves the continuous checking of the method's internal consistency and completeness throughout its development.
2. *Application evaluation* is about the assessment of the usability (or feasibility and practicality) of the proposed method and investigates whether the method can be used in the situation for which it was intended.
3. *Success evaluation* is about the assessment of the usefulness of the proposed method and identifies whether the support contributes to an improvement of the success factor.

Support evaluation is proposed for all four DRM stages and corresponds to *verification,* which is a continuous internal process (IEEE 2012). Application and Success evaluation are suggested for the final stage in the DRM cycle, *Descriptive Study II,* and correspond to *validation*, which involves external acceptance and suitability of the proposed support (IEEE 2012). In the following three subsections, the results of these evaluations will be presented for the FBS Linkage method.

5.1 Support evaluation

Support evaluation refers to the continuous verification to check that the method fulfils the requirements. Especially because during the stages of task clarification and conceptualisation descriptions of the method at different levels of detail are generated, it is required to ensure that each part at one level of detail is addressed by some part at the other (consistency) and to ensure that each part intended to be addressed by the method is indeed addressed (completeness). The internal consistency and completeness of the FBS Linkage method has been continuously checked and improved throughout its development. The FBS Linkage method has been regularly presented to experts from both academia and industry and continuously improved and extended based on their feedback. Smaller models were first built and tested for a hairdryer (Hamraz et al. 2012a) and a simplified diesel engine (Hamraz et al. 2012c).

5.2 Application evaluation

To evaluate the method's feasibility to complex products, two very different case examples were chosen – a diesel engine design as presented above, dominated by mechanical behaviours, and a scanning electron microscope (SEM) design, dominated by electron-optical behaviours. The method was feasible for both designs with an effort of 6 to 7 person-days (Table 4). Considering the re-use and modification potential of the model, this effort is relatively low and justifiable. In summary, the application evaluation can be rated as positive.

Table 4: Effort of FBS Linkage model building

No	Task	No of people involved		Time in hours		Effort in person-hours (= No of people x Time in hours)	
		Diesel engine	SEM	Diesel engine	SEM	Diesel engine	SEM
1	Decompose the product	2	3	2.0	2.0	4.0	6.0
2i	Map the structural layer S	2	3	5.0	3.0	10.0	9.0
2ii	Map the behavioural layer B	2	3	3.0	2.0	6.0	6.0
2iii	Map the structure-behaviour (S-B) links	1	1	3.0	2.0	3.0	2.0
2iv	Map the functional layer F	2	3	7.0	4.0	14.0	12.0
2v	Map the function-behaviour (F-B) links	2	2	3.0	3.0	6.0	6.0
3	Quantify FBS links	2	3	5.0	3.0	10.0	9.0
4	Compute combined change risk	1	1	2.0	2.0	2.0	2.0
	Total					**55.0**	**52.0**

5.3 Success evaluation

The proposed method aims to provide a more pro-active management of ECs. Ideally, the usefulness of such a predictive tool is evaluated in practice based on present data. This could be done, for instance, by applying the FBS Linkage model to present change cases and contrasting the outcome against the situation without the model. However, such a live evaluation would require a pilot-implementation which poses a risk to companies, and therefore, is often not feasible in practice. Researchers get round this problem by using test groups (see e.g. Clarkson and Hamilton 2000; Wyatt et al. 2012).

Alternatively, the performance of prediction tools can be evaluated based on historic data. For the model here, this would require historic change cases and a contrasting of predicted change paths to actual change paths. This too is difficult in practice because the reconstruction of historic change paths depends on the available change records. To be able to do so, the change request record has to differentiate between initiated and propagated changes and include information about change initiators and followers (see e.g. Giffin et al. 2009). Due to this challenge, developers of EC prediction tools test their tools against hypothetical change scenarios, often using toy examples and case-by-case tests (see e.g. Cohen et al. 2000; Keller 2007; Ollinger and Stahovich 2004).

To evaluate the performance of the FBS Linkage method, the following assessments were undertaken: (1) case-by-case tests of exemplar changes, (2) statistical analysis, and (3) verbal feedback evaluation by industry experts.

(1) Case-by-case tests based on exemplar samples of change cases were performed for the diesel engine model. These tests were performed using the overall model network and matrix. As these diagrams are too large to be depicted in a readable size here, references to the subparts are included for the following exemplary change path: initiated change to the *Geometry of the Crankshaft (Ge05)* → *Mechanical Behaviour of Crankshaft (Me05)* (Figure 14) → *'F9 Translate piston down'* function (Table 3) → *Mechanical Behaviour of Piston (Me03)* (Table 3) → *Material of Piston (Ma03)* (Figure 14). This could be a change case of downsizing the *Crankshaft* dimensions to save material cost. Such a downsizing results in a reduction of its mechanical strength and subsequently in a reduction of the parameters of *F9*. This, in turn, could be used to reduce the strength of the

Piston by changing to a lower quality material to save more material cost. In this case, the last two steps of the propagation path are rather optional; if the *Crankshaft* dimensions were to increase, they would probably be necessary to support the higher forces. In the numerical change propagation analysis, the preference of such options would be considered when estimating the likelihood of change propagation. The change propagation paths that the model suggested for the exemplar change cases were found to be causally reasonable. Furthermore, to validate the numerical change propagation results of the model, the aggregated combined risk DSM from Figure 20 was investigated in more detail. The third author, who has more than five years of expertise in diesel engine development, checked the risk values exemplarily for a few components, where he has expertise, against his expectations and found them to be plausible.

(2) An alternative analysis was performed to investigate the method's change prediction capability, one of the criteria against which EC methods can be assessed. This requires the methods to consider all potential propagation paths between any two product elements, and thus, avoid hidden dependencies. The more propagation paths are captured within the model, the fewer dependencies remain hidden, and consequently, the higher are the resulting linkage values. Thus, assuming that the model's accuracy is predetermined (model accuracy was tested in (1)), the resulting average linkage value (or here: the average combined risk value) correlates with the method's prediction capability. The higher the average linkage value is, the more propagation paths between any two elements are considered in the model, and thus, the better is the prediction capability of the method. While the average linkage values can run from 0% to 100%, the prediction capability has to be judged for each model individually and relative to the average direct risk value (and not relative to 100%).

To examine how the layers contribute to the prediction capability of FBS Linkage model, the average combined risk value was calculated for three model variants: (1) single layer change propagation using only the structural layer (Forward CPM(S)), (2) double-layer change propagation using the structural and behavioural layers (Forward CPM(BS)), and (3) triple-layer change propagation using the structural, behavioural, and functional layers (Forward CPM(FBS)). To obtain the combined risk matrices, the Forward CPM algorithm was applied considering 6 steps of propagation. Furthermore, as baseline, the direct change risk matrix (i.e. no change propagation) was considered. The results within the structural layer (i.e. SS MDM) were aggregated to the component level using the maximum operation. Figure 22 summarises this comparison for the diesel engine along with the two other examples of a hairdryer and a SEM.

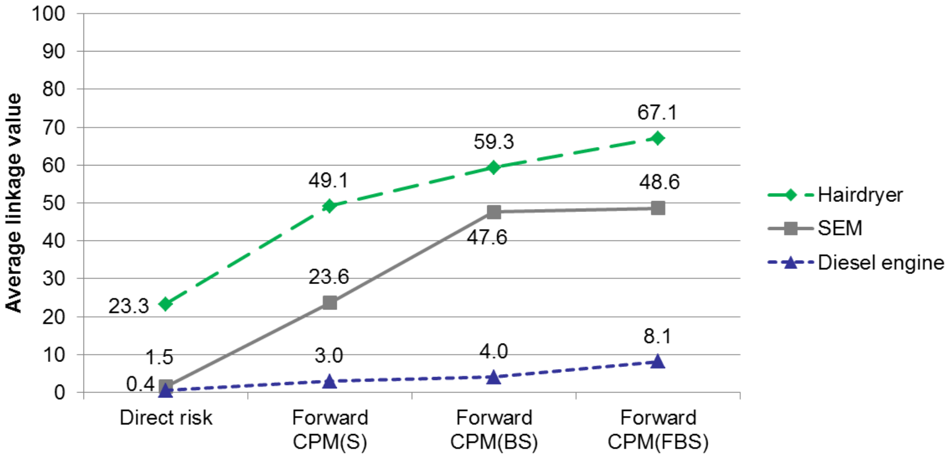


Figure 22: Comparison of single-layer to multi-layer change propagation analysis

For all three designs, the distribution shows steadily increasing values: the more layers are considered in the change propagation model the higher the average linkage, that is, the more propagation paths are revealed. This shows how each layer adds more information to the model and underlines the benefit of a multi-layer approach towards a single-layer approach. However, as most single-layer approaches such as CPM consider influences from other layers implicitly in the linkage values of their single-layer, it is difficult to compare multi-layer methods to single-layer methods directly.

The absolute levels and the runs of the curves are different for each design. The absolute level correlates with the density of the input matrix reflected in the direct risk value. The matrix density of the smaller hairdryer model is much higher than the matrix density of the SEM and diesel engine. This results into an overall higher absolute level of the hairdryer curve. The direct risk bar could be used as the baseline to normalise the levels. The run of the curve describes how many additional connections between the structural attributes become available when considering additional layers. The gradient depends on the characteristics of the three different layers of the network. For the SEM, the inclusion of the functional layer in addition to the behavioural layer does not add significantly new connections between the structural elements whereas for the diesel engine, this extension doubles the average linkage value.

(3) An evaluation workshop was conducted at Dagenham Diesel Centre of Ford Motor Company with two Technical Leaders. Paul N. Turner has been working in engine product development for 24 years and held different positions, including component engineer. His responsibilities focus on future engine designs and the acquisition of new technologies to meet future requirements. Mr Turner leads the technical development of mechanical systems for gasoline and diesel engines. Sean G. Harman has been working in engine product development for 23 years. His past roles include engineering of both engine components and systems. His current role focuses on performance systems and involves design lead and system integration. Mr Harman leads the technical development of fuel and air path systems, and components in support of the future gasoline and diesel engine developments.

The first author presented the method and demonstrated the corresponding model to the industry experts. A following discussion and questions and answers session ensured that the experts sufficiently comprehended the method, before they were asked to give their feedback. The workshop was recorded and transcribed. The transcripts were sent to Mr Turner and Mr Harman by e-mail to ensure that their arguments were completely and correctly transcribed.

Both Technical Leaders were overall convinced by the FBS Linkage method. They approved the breakdown of a design into the three layers of functions, behaviours, and structures, and they saw some potential useful applications of the method to support pro-active management of ECs in their own organisation or similar global organisations and pointed out some directions for further improvement.

Mr Harman praised the method's procedural approach: *"The concept is very good. […] Having a methodology and a structured approach that gets everyone to follow the same steps is a good thing. Anything that is left to too much interpretation will end up with a very complex system with many different types of results."* Mr Turner noted: *"Vehicles and engines are getting more and more complex. System interactions are the things that we* *generally struggle with. We are quite good at designing a crank shaft - we do it for hundred years. [..] But the systems interactions are very difficult to manage; that's where such a linkage model is very useful."*

Both Technical Leaders emphasised the use of this method to support communication and pro-active management of ECs in multinational companies, where component designers may be located all over the world, and so the changes may propagate around the world. Mr Harman explained: "*If you have to change the specifications of one component in your area, the person affected by that change, in a big organisation, might have no way to know that the change is happening. So, if your model can use the existing linkages to flag up the change to all affected designers, each of them would be able to react early. […] There are other methods to flag up changes, […] but you never know how that effect is. Being able to quantify the effect is an advantage. If the structure in this model is set up correctly, you could minimise the number of false alarms and maximise the attention needed. […] For the automotive industry, that would be a useful bonus for the amount of work that you have to put in to develop such a method."* Mr Turner added: *"Today, we have a rigorous change management process trying to make people go through the steps and identify all the effects. […] The component engineer is then responsible for presenting that; but it is incumbent on the people who think they are affected to turn up to the meeting and determine whether they are affected or not. If they don't turn up, or they don't think they are affected but they are. […] only later will people realise 'Oops! A change has happened we didn't know'"*.

Mr Harman noticed that *"Breaking down into function, behaviour, and structure is an excellent idea. At the moment, we look at block diagrams and try to get the linkages between various components and systems. We try to look at the effect from one to another in terms of flows of energy, information, and material. Understanding how functions, behaviours, and structures are interrelated is a level of refinement which I think is very useful."*

Mr Harman regarded the familiarity of the method as an advantage for acceptance in industry: *"We have looked at flows of any form of energy, material, and information between components at the engine level. […] I can see the systems that we do at the moment being quite useful in terms of delivering input for this model, so we are not coming straight from scratch. […] some of these functions could link in into our current models such as our combustion model and use that as input. There are quite well-known function trees, for instance the relations between material properties and surface areas for constant rotations. Today, we look at these functions in isolation and then try to work out what else might have an impact."* He then pointed out the importance of input flexibility for such a model: *"You probably find that a lot of information is already available in the database. It then comes back to getting the information in the right structure. […] I think making sure that the data capture is fit for use for all different types of information would be very useful. Just to ensure that people can take existing information and transfer it into the model rather than having to start from scratch."* Mr Turner supported this argument and saw it as an essential area for further improvement of the method: *"For accurate change prediction to work effectively, I would recommend that the model is linked to real data to continually update and learn as it is being used, based upon actual events. […] Expert estimations are fine to get it started, but then in reality, the actual data can surprise you. Having a methodology to refine that input and evolve the model is mandatory."*

Mr Harman highlighted the Planning Office as a potential good area to use this model for project size estimation: *"If we had a reasonable model to start with, we could perhaps put in a level of change or define a new function. So, we know what the function is and we know what we need to change to get that function; and we can put that in [the model] and that would tell us what the knock-on effect would be to the whole engine. I'm sure with a* *certain amount of expert input from the cost estimating finance side you could probably start estimating the size of the program based on the change."*

Mr Turner emphasised it potential use to compare and optimise between different engines: *"Potentially, if you take a diesel engine, and apply this to different types of engine. You can compare what's happening on Engine 1 versus Engine 2 versus Engine 3. It might be a useful way of saying 'well actually, something is going strange on Engine 2 because we are seeing a higher occurrence of these sorts of linkages. Is that a design weakness or a usage condition which is causing more problems on this engine?'"*

Both evaluators appreciated the flexibility of the model. Mr Harman referred to the different types of input: *"For a mechanical system like an engine, quite a few of these links are based on laws of physics and therefore quite easy to be more accurate in that relationship – it is not just an estimate – there is often an equation behind it. [...] I think this model could be fairly accurate for critical attributes and vaguer for secondary attributes of the engine."* Mr Turner referred to the different levels of detail: *"Rather than doing it for every component, you might want to stick at the systems level and then focus on the key systems, and break them down further."*

They briefly checked the functional block diagram of the engine and but did not have enough time to check the model and its results in more detail. However, with regard to model accuracy and validation, Mr Turner suggested: *"You have to create the model. You have your expert input as starting point. You need to then use the model to see how the changes actually flow through the system and record the change paths in your change control system. We don't record that today; it would require some system type changes in how we operate the company. You have to do something like that to refine, update, and validate the model."*

Mr Harman noticed an application limitation of the method: *"If the key enabler for the tool to work is having the expert input, I think, if you picture that for a very large system (i.e. the entire vehicle), you won't find anybody who is expert enough to give you that information and you have to get too many experts together; and if you get two engineers in one room, you get four solutions. You might want to think about where to pitch the models size. For a diesel engine, which is quite a complex thing to do, we are probably talking about half a dozen experts to get enough detail. So, that doesn't seem to be beyond the level to make it. The bigger you make it the more expertise you need or the higher level you have to go in terms of linkages; the higher the level the less resolution you get; and there is a trade-off between how much time you spend to develop the model and how much benefit you get from it. In terms of evaluating the model, you might want to think about how you would perhaps look at the input versus the resolution of the model, and then, try to have a metric of how much accuracy you need vs. how much input you need [...]. If you pitch it [the amount of input] too high it will be a too big task and you won't get enough input; if you pitch it [the amount of input] too low you won't have enough resolution in order to be useful. [...] So you have an upfront requirement for the model."*

Mr Turner concluded: *"The thing that's making me think is how this would integrate with our current quality tools; and could it enhance our current quality tools? I think the answer is probably yes [to both]. It is just making sure that it is aligned with our operating practices globally. I think there is a merit to do this. You have to start somewhere, start small and then expand and grow. I think this method could do that. Particularly, as we are now trying to think in a system way and look at the interactions between components, this model potentially has an opportunity to help construct some of that. The hard bit in reality is always 'how do you actually do it to* *make it an automated tool?' If it's manual, it's never used. If it's a tool that is straight forward and easy to use and interlinking to existing systems, then this potentially could work very well."*

In summary, the success evaluation shows that overall the method contributes to an improvement of EC management, and thus the evaluation can be rated as positive. However, it has to be noted that this is only an initial evaluation. Next, for a more practical evaluation, experiments with test groups could be run, involving a pilot implementation of the method and its application to exemplary change case simulations. Eventually, for a complete success evaluation, the method has to be implemented as a software tool in a company and applied to present change cases. The outcome can then be contrasted against the situation without the tool to evaluate the actual impact.

6 Conclusion

Engineering changes are raised throughout the product lifecycle and can cause severe profit losses if not managed sufficiently. As product development times are continuously decreased, the management of such changes is becoming more important.

This paper has presented our continued work on the FBS Linkage method - a multi-domain change propagation model based on the concepts of functional reasoning and the CPM. Four contributions of this paper can be highlighted: First, we presented a comprehensive review and comparison of the three seminal function-behaviour-structure ontologies highlighting their key characteristics and discussing their shortcomings in the context of change modelling. Second, we used the previous comparison to develop a function-behaviour-structure scheme which is more practical for change modelling and incorporated this scheme into our FBS Linkage model. Third, we described the modelling technique and applied it to develop a FBS Linkage model for a diesel engine. Fourth, we evaluated the FBS Linkage method.

The diesel engine was decomposed into 42 components. For each component, 4 structural and 3 behavioural attributes were defined and their elements were linked to each other. A functional block diagram comprising 40 subfunctions was developed and the FBS Linkage scheme was completed by linking each subfunction to the responsible behavioural elements. Subsequently, the FBS links were quantified and a combined change risk matrix was calculated using the Forward CPM algorithm. The numeric change risk model was used to generate component-level risk profiles and prioritised change risk lists.

The evaluation of the FBS Linkage method was overall positive and comprised three parts:

1. The Support evaluation continuously ensured internal consistency and completeness of the method.

2. The Application evaluation showed that the method can be used in the situation for which it was intended.

3. The Success evaluation showed that overall the method contributes to an improvement of EC management and highlighted areas of further improvement.

The expert panel from industry found that *"The concept is good"* and praised the systematic approach. They liked the extension of CPM to include more details and found that *"Breaking down into function, behaviour, and structure is an excellent idea."* Both Technical Leaders highlighted the potential benefit of the FBS Linkage method to support communication and pro-active management of ECs in a global organisation. On the downside, they criticised the intensive manual work required for building a model. They suggested a few improvement ideas for future work. These include the linking of the model to available information databases and the capability of the model to capture change paths and automatically use them to continuously learn and improve.

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