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FBS LINKAGE MODEL – TOWARDS AN INTEGRATED ENGINEERING CHANGE PREDICTION AND ANALYSIS METHOD

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1. Introduction

Engineering changes (ECs) are unavoidable and occur throughout the lifecycle of products. Due to the high interconnectivity of engineering products, a single change to one component usually has knock-on effects on other components causing further changes. The impact of such changes propagates beyond the product domain to the design process domain and significantly affects the success of a product by increasing development cost and time-to-market. Managing such ECs is thus essential to companies and its improvement remains a challenge for managers and researchers alike. While existing change management methods focus on the product domain, there is a lack of design process-oriented methods.

This paper presents a framework aimed at improving engineering change management (ECM) through integration of product and process domains and elaborates its first building block – the FBS Linkage model, a novel, multi-layered change prediction and analysis method in the product domain based on the FBS model [Rosenman and Gero 1998]. The remainder of this paper is structured as follows. Section 2 provides the background for this research including an introduction to ECM and a review of relevant tools and methods. Section 3 presents the proposed integrated framework and subsequently develops the FBS Linkage model. Section 4 presents an initial case study to demonstrate the application of the proposed method. Finally, Section 5 presents the paper summary and conclusion.

2. Background

2.1 The increasing importance of ECM

In today's customer-driven and dynamic markets, ECs cannot be avoided. They can be triggered by company internal or external sources for the purposes of variation or improvement, and correction [Jarratt et al. 2011]. Well-known examples of ECs are those required to improve an existing product. This applies to the majority of products since most designs evolve over time by continuous product improvement. ECs are not limited to the development phase but occur throughout the lifecycle of products. The continuously decreasing *development times* combined with increasing *complexity* in engineering systems and their environment have increased the potential occurrence and impact of ECs. Therefore, managing such changes has become an essential discipline with significant impact on a company's competitiveness. Since ECs propagate, dealing with them is not straightforward. As their implementation takes place in the process domain and requires resources, their impact is not limited to the product domain, but can also comprise the process and the organisation domains. Thus, in a wider context, change propagation refers to the knock-on effects of ECs within and across the product, process, and organisation domains. Its resulting impact can be very severe as it often entails both cost increases as well as schedule delays.

2.2 Methods and tools for EC prediction and analysis

Many methods and tools trying to model EC propagation and support EC prediction and analysis have been developed, notably the Change Prediction Method from [Clarkson et al. 2004], RedesignIT from [Ollinger and Stahovich 2004], and C-FAR from [Cohen et al. 2000]. Others can be viewed as variations to these. It is important to note the differences between these three approaches. The Change Prediction Method focuses on components and relies on structural relations between them as cues for change propagation [Clarkson et al. 2004]. It is a probabilistic method which shows the risk imposed on other components if one component changes. RedesignIT ignores components and focuses on physical quantities (e.g. shaft temperature) which describe system behaviours [Ollinger and Stahovich 2004]. It supports causal reasoning about change propagation between those physical quantities. C-FAR examines the attributes of the key elements of products (e.g. type and volume of a liquid) and how they are linked to attributes of other elements [Cohen et al. 2000]. However, all three methods focus on certain aspects of the product domain and do not capture all dependencies. Due to this shortcoming, the models bear so called *'hidden dependencies'*. Furthermore, they model change propagation within the product domain but do not consider the process domain; they provide no advice on how to implement ECs most efficiently. Thus, there is a need for a framework which allows comprehensive modelling of ECs in the product and process domains in such a way that they can be interlinked into an integrated change prediction and analysis method.

2.3 The FBS framework for product modelling

The product domain in the context of manufacturing is concerned with the object of design: the artefact, which as an umbrella term may refer to a single part, a component, an assembly, a system, or a whole product. Artefacts are characterised by their constituent elements and interconnections between them. The elements of an artefact can be specified as structural, behavioural, and functional elements; the interconnections between them are realised by parameters which may refer to interfaces, physical quantities, and flows of information, energy, and mass. Gero and colleagues have developed the FBS framework, a product representation based on the decomposion of a product from its functions over its behaviours to its structure [Rosenman and Gero 1998]. Structure exhibits behaviour; behaviour effects function; and function fulfills a purpose. Accordingly, the product domain can be structured into three sub-domains or layers [Rosenman and Gero 1998]:

1. The structural layer includes definitions of the material, form, and dimensions of the artefact, its constituent components, and their arrangement and connection to each other. A structural description is sufficient to construct the artefact. It includes the necessary information about the artefact's explicit parameters which a designer directly determines in order to generate a physical solution to an abstract problem.
2. The behavioural layer includes the description of the artefact's potential behaviours in response to its environment. Behaviour is defined as a description of the artefact's actions or processes in response to its environmental conditions. Behaviours are derivable by means of a physical theory from the structure of the artefact and possibly some properties of the environmental conditions.
3. The functional layer describes the artefact's role (i.e. intended purpose). The important role of function in design is generally accepted, but its definition, however, remains ambiguous and controversial with a multilateral spectrum of meanings depending on the field of usage. In this research, function is used in the context of the FBS model and defined as "what [the artefact] does" as opposed to "what it is" (structure) and "how it does" (behaviour).

2.4 Process modelling frameworks

While conventional processes can be described by dependent tasks (with sequential order) and independent tasks (with parallel order), product development (PD) processes predominantly consist of interdependent tasks (with coupled order) [Eppinger et al. 1994]. They are characterised by low standardisation and repetition, high share of creative work and multidisciplinary interactions, high uncertainties and risk, ambiguity, many iterations, and manifold interdependencies among tasks, their results, and people [Browning and Ramasesh 2007]. Many modelling frameworks exist for supporting PD process planning by capturing and representing design activities, and/or parameters, and their interdependencies (for a review see [Browning and Ramasesh 2007]. Each modelling framework highlights certain aspects of the process at the expense of others. To find a suitable framework for modelling of ECs, a comparison of well-established modelling frameworks has been made:

Table 1. Comparison of modelling frameworks in terms of their use for design processes

Criteria	CPM/ PERT	IDEF0	DSM	IDEF3	Petri nets	ASM (Signposting)
Process elements	Tasks	Tasks, control signals, resources	Tasks	Tasks, object states, junctions	Tasks, parameters (availability)	Tasks, parameters (quality)
Precedence/ dependency	Precedence	Dependency	Dependency	Precedence	Precedence	Both
Hierarchies	No	Yes	No	Yes	No	Yes
Characterisation according to relevant key characteristics for design processes						
Iterations	No	No	Yes	Yes	Yes	Yes
Probabilities/ uncertainties	No	No	Possible	No	No	Yes
Parameter refinement	No	No	No	No	No	Yes
Alternative routes	No	No	Yes	Yes	Yes	Yes
Guidance for optimal task selection	No	No	No	No	No	Yes
Evaluation in terms of general aims of process models (1: low, …, 5: high)						
Elicit and capture expert knowledge	2	1	3	3	3	4
Visualise knowledge	4	4	4	3	3	3
Support process improvement	1	1	4	2	2	4
Support planning	4	2	2	2	2	2
Support process development and automation	1	2	2	2	4	4

The evaluation is conducted on a scale from 1 (low) to 5 (high) based on the assessment of the authors. As the list shows, CPM and IDEF0 do not feature any of the key characteristics of design processes. Nevertheless, because of their very good visualisation, they can be used for simple or high level design processes with no iterations. Although DSM is restrictive in terms of parameter refinement and guidance for optimal task selection, it allows very convenient elicitation and compact visualisation of knowledge about the process. The matrix-based representation is advantageous for computing and application of algorithms to determine optimal process architectures. Thus, DSM can be used complementarily to other frameworks in order to provide an alternative process visualisation and optimise the process architecture. Petri nets and IDEF3 are both usable for design process modelling. However, they are restrictive when modelling probabilistic task outcomes, uncertainties, and parameter refinement. Although both can capture iterations, they neither do provide guidance on how to manage them successfully nor support optimal task selection and dynamic task integration and re-ordering. Applied Signposting Modelling (ASM) developed by Wynn et al. [2006] supports all relevant key characteristics of design processes and provides a good basis for product-process integration due to its focus on parameters.

3. A framework for integrated EC prediction and analysis using FBS and ASM

3.1 Framework requirements

Drawing on insights of literature in ECM, the following requirements can be listed for an integrated change prediction and analysis framework:

1. Scope of the framework – The framework should support modelling of different ECs and their propagation; in detail, it should enable modelling of: (1) the whole lifecycle of ECs along the generic EC process from when they are raised, to decision support, execution, and documentation, (2) initated ECs and emergent ECs raised throughout the product lifecycle, and (3) EC propagation within and across product and process domains.
2. Product modelling – The framework should support a comprehensive modelling of ECs within the product domain; in detail, it should enable modelling of: (1) the product's functional, behavioural, and structural layers, (2) the links between these layers, and (3) the attributes and parameters within these domains.
3. Process modelling – The framework should support a comprehensive modelling of ECs within the process domain; in detail, it should enable modelling of: (1) the network of design tasks, parameters, and resources, (2) the corresponding product attributes and parameters, and (3) change propagation within the network in form of propagation of rework.
4. Integration of product and process domains – The framework should provide an interface between the product and process domains to interlink both into an integrated method.

3.2 Overview of proposed framework

Based on these requirements, a framework which uses the FBS approach in the product domain, the ASM approach in the process domain, and parameters to integrate both domains has been developed:

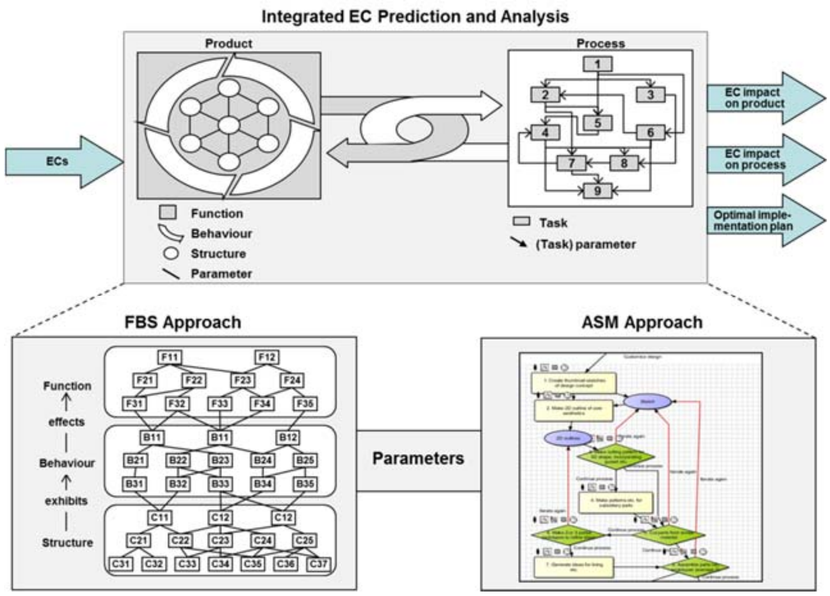

Figure 1. Integrated EC prediction and analysis – framework overview

As depicted in Figure 1, the proposed framework addresses the requirements listed above: (1) It captures all types of initiated and emergent ECs and models their propagation within and between the product and process domains. (2) The FBS feature allows a holistic presentation of the product in terms of its structure, behaviour, and functions and thus supports comprehensive EC modelling. (3) The ASM feature supports parameter-based modelling of design process and captures detailed process information to support comprehensive EC modelling. (4) The framework supports parameter-based product and process modelling and uses parameters to integrate both domains.

3.3 The FBS building block - the FBS Linkage model for modelling of change propagation in the product domain

The FBS approach allows a holistic modelling of products in terms of their structural, behavioural, and functional layers. However, it has not been used for modelling of ECs within the product domain yet. This is the first reported attempt to model change propagation on the FBS model. For this purpose, a modified FBS model targeted specifically at ECs has been developed – the FBS Linkage model. As depicted on the left side of Figure 2, this model captures all structural, behavioural, and functional elements and their interrelations. Using the model, change propagation can be described within and across the three product layers based on the following assumption:

- Assumption 1 (Change propagation paths) – ECs propagate along the links in the FBS Linkage model.

As the FBS linkage model includes all relations between structural, behavioural, and functional elements, hidden dependencies do not exist and thus two elements can only influence each other if there is a (direct or indirect) link between them. A change path can be decomposed in up to five path sections, which describe possible change propagation steps:

- Path section 1: Change propagation within the structural layer.
- Path section 2: Change propagation between the structural and behavioural layers.
- Path section 3: Change propagation within the behavioural layer.
- Path section 4: Change propagation between the behavioural and functional layers.
- Path section 5: Change propagation within the functional layer.

3.3.1 Change propagation within the structural layer

Structure defines what the artefact exists of. The structural layer includes the components, their ontology, and structural links or dependencies between them. In order to develop a structural layer which can be used to describe change propagation, the following three assumptions are made:

- Assumption 2 (Components) – A product can be decomposed into its components.
- Assumption 3 (Structural elements) – Each component can be defined by a set of independent structural elements (explicit component attributes): controller (Ctr), geometry (G), material (M), colour (C), and surface finish (S).
- Assumption 4 (Structural links) – There are structural links between structural elements which translate structural requirements of the product into the component level, e.g. the product dimension requirement constrains the dimensions of its components. Structural links exist only between structural elements of the same type of different components, e.g. in Figure 2 the geometry of component 3 is linked to the geometry of component 4, 5, and 6. In general, the links in the structural layer are directional and may be asymmetric, i.e. the geometry of component 3 may influence the geometry of component 4, but not vice versa.

The idea of product decomposition into smaller parts (Assumption 2) is based on a common principle of engineering to break down complex problems into smaller parts that are more easily manageable. Assumption 3 is closely linked to the concept of explicit design attributes from [McMahon 1994]. The five structural elements listed represent generic attributes which are applicable for most 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 attributes of different types (e.g. M↔S) can be neglected compared to the dependencies between structural attributes of same types across components (e.g. G of component 1 ↔ G of component 2). Assumption 4 is a logical consequence of Assumption 3; as the five types of structural elements are considered as (structurally) independent, they cannot influence each other in the structural layer. These relations are depicted in Figure 2. In addition, the structural layer can be represented in a DSM, where the structural elements are mapped to DSM elements and the interlinking structural requirements to DSM dependencies. The diagonal cells are empty because self-dependencies are not considered.

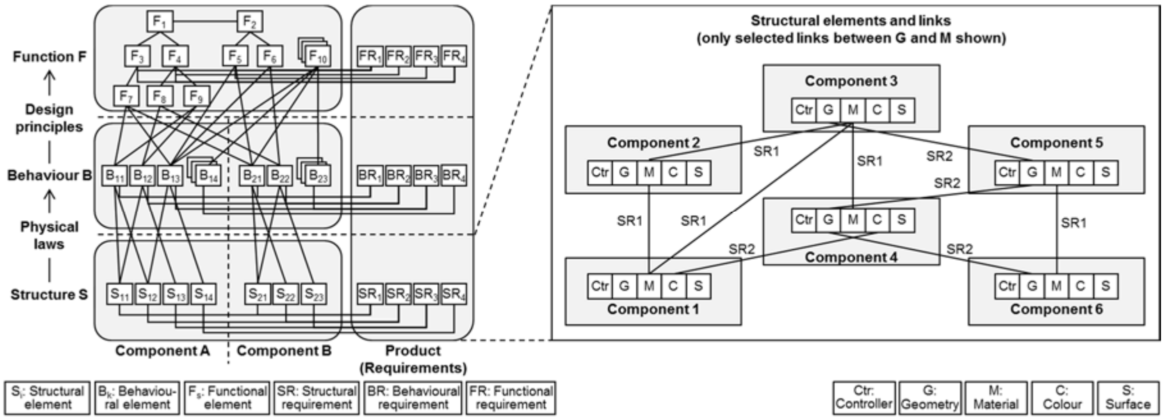

Figure 2. FBS Linkage model (left), change propagation within the structural layer (right)

Within the structural layer, paths of different order between two given elements are possible. Direct links (1st-order paths) can be read immediately from the DSM and are responsible for direct change propagation. Indirect links (2nd or higher order paths) can be calculated for numerical DSMs by applying matrix multiplications, or using the algorithm of the Change Prediction Method; they are responsible for indirect change propagation. As the five types of structural elements are considered as independent, direct links may exist only within each type, e.g. a change in geometry may only propagate to other changes in geometry. Thus, indirect propagation in the structural layer may only take place within each of these five sub-networks.
Assumptions 3 and 4 hold similarly for the behavioural and functional layers.

3.3.2 Change propagation between the structural and behavioural layers

The links between the structural and behavioural layers are modelled based on Gero's FBS model:

- Assumption 5 (Causality of links from the structural to the behavioural layer) – Behaviour is realised by structure and derivable by means of a physical theory from the structure of the artefact and possibly some properties of the environmental conditions. Thus, the links from the structural layer to the behavioural layer are causal.
- Assumption 6 (Relation between structural and behavioural elements) – The relation between structural and behavioural elements is of type n:m. Thus, within a component, a behavioural element may depend on one or more (1, 2, …, n) structural elements of different types, and a structural element may influence one or more (1, 2, …, m) behavioural elements.

Assumptions 5 and 6 hold similarly for the links between the behavioural and functional layers.

3.3.3 Possible change propagation paths

The following assumption is made to derive possible propagation paths.

- Assumption 7 (Implementation of ECs) – The implementation of changes always involves the structural layer.

This assumption is a logical consequence of the cause-and-effect relations between the layers. As the structural layer is at the very beginning of that reasoning chain, it must be the cause of all following effects. Thus, the implementation of changes must always involve the structural layer, i.e. all propagation paths must include at least the structural section (*Path section 1*). The implementation of ECs takes the form of "change structural attribute *X* of component *Y*", where *X* could be one of the five structural attributes defined earlier and *Y* any component. Furthermore, as the FBS Linkage model allows direct links only between neighbouring layers, five change path types can be differentiated according to the path sections they include:
These change path types characterise the propagation paths in terms of covered path sections. Within each section, several steps of indirect propagation may take place. For instance, within Path section 1, the path could be $S_1 \rightarrow S_2 \rightarrow S_3$; and within Path section 2, the path could be $S_1 \rightarrow B_1 \rightarrow S_2 \rightarrow B_2 \rightarrow S_3$. When

a path crosses itself, e.g. $S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_1$ it builds a loop which implies that an element affects itself and the number of possible steps becomes infinite. To avoid this, another assumption is made:

- Assumption 8 (Exclusion of change path loops) – Change paths do not include any loops.

Excluding loops allows each element to appear at maximum once in a propagation path. Infinite propagation paths are avoided and the number of steps a path can take is limited to the number of total elements minus one, i.e. (*n-1*). In practice, loops can appear as a form of iterations towards the final result. Thus, when calculating effort based on this assumption, its effect could be neutralised by including the effort for all follow up iterations within the initial effort values.

Table 2. Five change path types

Path type	Containing path sections
Type 1	Path section 1
Type 2	Path section 1 & Path section 2
Type 3	Path section 1 & Path section 2 & Path section 3
Type 4	Path section 1 & Path section 2 & Path section 3 & Path section 4
Type 5	Path section 1 & Path section 2 & Path section 3 & Path section 4 & Path section 5

3.3.4 Parameter-based integration of the FBS Linkage model to the ASM building block

Using these eight assumptions discussed above, EC propagation can be modelled within the product domain. The model can be applied to calculate probabilistic linkages between elements prior to appearance of ECs or to conduct causal change propagation analysis on appearance of ECs. In both cases, the respective change propagation paths include structural elements as noted in Table 2. These elements represent structural attributes or parameters that need to be changed in order to implement an EC and thus provide an interface to build a bridge to the process domain.

4. Case study

The proposed framework is composed of two building blocks interlinked by parameters: the FBS approach and the ASM approach. The first building block has been specified into the FBS Linkage model. This section presents its application to a hairdryer.

4.1 The product – hairdryer

The hairdryer consists of six components as shown in the explosion diagram in Figure 3. Its main functions can be described as "generate hot air flow" and "control hot air flow".

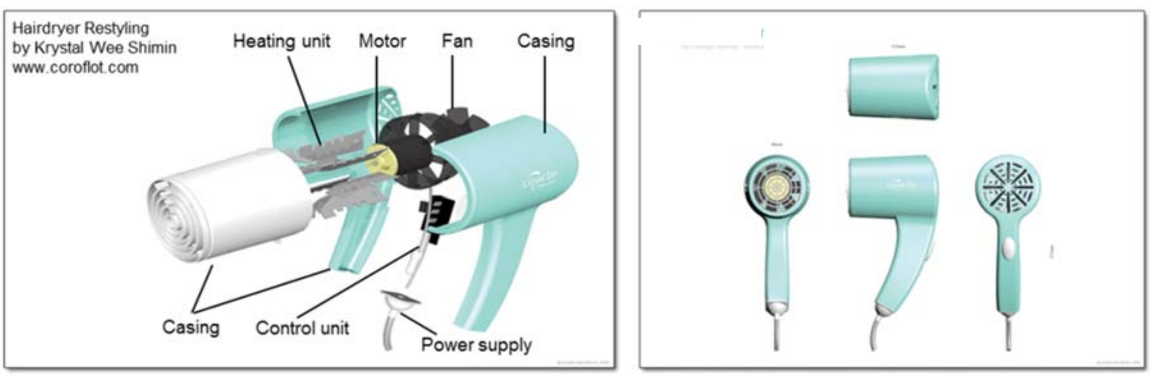

Figure 3. Explosion diagram and different views of the hairdryer

The choice of a hairdryer for this case study is justified by two reasons:

- Appropriate degree of complexity. The product simplicity eases understanding and model building, but still embodies several physical laws and design principles which allow evaluation of the model, testing of hypotheses, and demonstration of feasibility.

- Availability of modelling experience. The product has been chosen by other researchers within the authors' group to develop theories and demonstrate models. Thus, there is a good knowledge base about the product available which helped build the model.

4.2 Building of the FBS Linkage model for the hairdryer

The FBS Linkage model has been built top-down and bottom-up simultaneously. Functional decomposition and functional modelling methods such as the method from [Stone and Wood 2000] can be applied to determine relevant sub-functions. Five functional, 25 behavioural, and 26 structural elements were defined. The functional elements were linked to the behavioural elements which in turn were linked to structural elements. As a result, the following FBS Linkage tree has been developed:

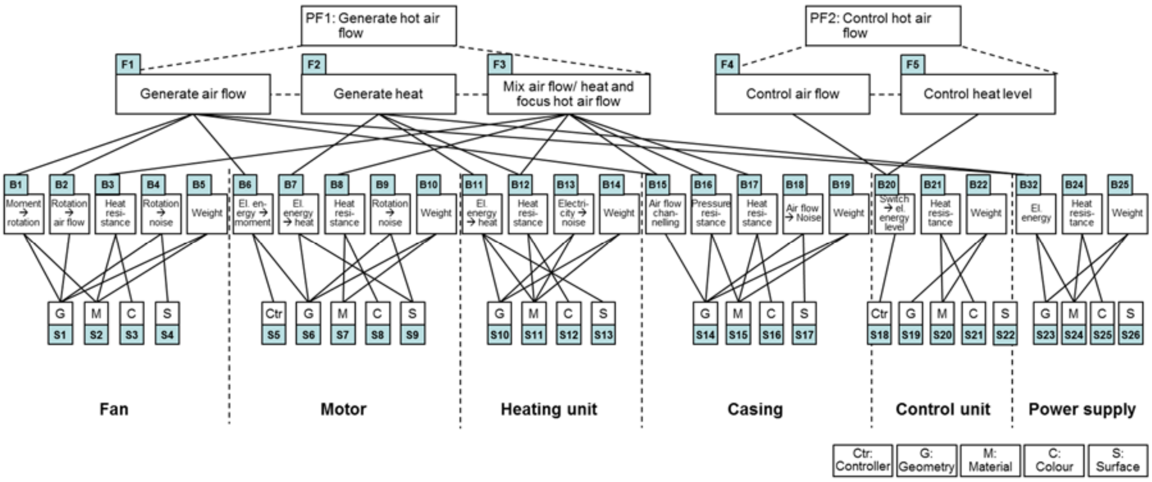

Figure 4. FBS Linkage tree of the hairdryer

In addition to the tree, these inter-layer links were also represented in domain mapping matrices (DMMs). Intra-layer links, which are not shown in Figure 4 due to graphical clearness, were derived by considering dependencies between the elements and constraints posed on them by respective product requirements. They were represented in DSMs and finally composed with the DMMs into a multi domain matrix (MDM) – the FBS Linkage MDM.

4.3 Numerical analysis of the FBS Linkage MDM

For an initial numerical analysis, all links in the MDM were replaced with the linkage value of *1.0* and modified matrix multiplications which considered the exclusion of loops and self-dependencies were applied to calculate the numbers of 2nd-order and 3rd-order paths between the elements. These numbers were transformed into linkage values based on two assumptions:

- The linkage value between two elements decreases with the length of the path. As a first attempt, the decrease factor w can be calculated as a function of the order g: $w(g) = (1 / 2g)$, i.e. 0.5 for 1st-order paths, 0.25 for 2nd-order paths, and 0.125 for 3rd-order paths.
- For a given path-order, the number of paths between two elements is directly proportional to the linkage value between them.

The first assumption allows aggregation of linkage values of different orders. The relation between the linkage values and the length of the path has not been investigated yet. However, exponential decreasing factors are reasonable because they relate to path multiplication rules. The second assumption allows transformation of the number of paths of same order into linkage values. It is based on the idea that elements impact each other through existing links in the FBS Linkage model. Thus, the more links are available the higher is the impact.

Aggregated linkage values between all elements of the MDM were calculated. Exemplarily, the linkage values between structural elements are depicted in the following figure:

Hairdryer FBS Linkage model:			Fan				Motor					Heating unit				Casing				Control unit					Power supply				Total
Aggregated linkage values between structural elements			G	M	C	S	Ctr	G	M	C	S	G	M	C	S	G	M	C	S	Ctr	G	M	C	S	G	M	C	S	
			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	
Fan	G	S1		0.5		0.3	0.3	1.5	0.3		0.6	0.9	0.6	0.1	0.4	1.4	0.6	0.1	0.4		0.6	0.3	0.1		0.6	0.3	0.1		9.9
	M	S2	0.5		0.3		0.1	0.6	0.1		0.1	0.3	0.4	0.1	0.1	0.5	0.3	0.3			0.1	0.3	0.3		0.1	0.3	0.3		4.9
	C	S3		0.3				0.1		1.3	0.1	0.1	0.3	0.1	0.1	0.1	0.3	1.4				0.3	1.3			0.3	1.3		7.1
	S	S4	0.3					0.3			0.1	0.1	0.1		0.1	0.3			0.1										1.4
Motor	Ctr	S5	0.3	0.1				0.3								0.1			0.3	0.5									1.5
	G	S6	1.5	0.6	0.1	0.3	0.3		0.3		0.5	0.8	0.5	0.1	0.3	1.1	0.5	0.1	0.3	0.1	0.6	0.3	0.1		0.6	0.3	0.1		9.3
	M	S7	0.3	0.1				0.3		0.3		0.3	0.4	0.1	0.1	0.4	0.3	0.3			0.1	0.3	0.3		0.1	0.3	0.3		3.9
	C	S8			1.3				0.3			0.1	0.3	0.1	0.1	0.1	0.3	1.4				0.3	1.3			0.3	1.3		6.9
	S	S9	0.6	0.1	0.1	0.1		0.5				0.3	0.4	0.1	0.3	0.5	0.1	0.1	0.1			0.1	0.1			0.1	0.1		3.9
Heating unit	G	S10	0.9	0.3	0.1	0.1		0.8	0.3	0.1	0.3		0.8		0.5	0.9	0.5	0.1	0.3		0.5	0.3	0.1		0.5	0.3	0.1		7.5
	M	S11	0.6	0.4	0.3	0.1		0.5	0.4	0.3	0.4	0.8		0.3	0.5	0.9	0.4	0.3	0.1		0.1	0.4	0.3		0.1	0.4	0.3		7.5
	C	S12	0.1	0.1	0.1			0.1	0.1	0.1	0.1		0.3			0.1	0.1	0.1				0.1	0.1			0.1	0.1		2.0
	S	S13	0.4	0.1	0.1	0.1		0.3	0.1	0.1	0.3	0.5	0.5			0.5	0.1	0.1	0.1			0.1	0.1			0.1	0.1		3.9
Casing	G	S14	1.4	0.5	0.1	0.3	0.1	1.1	0.4	0.1	0.5	0.9	0.9	0.1	0.5		0.6	0.1	0.3	0.1	0.9	0.4	0.1		0.9	0.5	0.1		10.9
	M	S15	0.6	0.3	0.3			0.5	0.3	0.3	0.1	0.5	0.4	0.1	0.1	0.6		0.3			0.4	0.3	0.3		0.4	0.3	0.3		6.0
	C	S16	0.1	0.3	1.4			0.1	0.3	1.4	0.1	0.1	0.3	0.1	0.1	0.1	0.3					0.3	1.4			0.3	1.4		7.9
	S	S17	0.4			0.1	0.3	0.3			0.1	0.3	0.1		0.1	0.3				0.5	0.1				0.1				2.6
Control unit	Ctr	S18					0.5	0.1								0.1			0.5										1.3
	G	S19	0.6	0.1				0.6	0.1			0.5	0.1			0.9	0.4		0.1			0.3			1.0	0.4			5.1
	M	S20	0.3	0.3	0.3			0.3	0.3	0.3	0.1	0.3	0.4	0.1	0.1	0.4	0.3	0.3			0.3		0.3		0.3	0.3	0.1		4.5
	C	S21	0.1	0.3	1.3			0.1	0.3	1.3	0.1	0.1	0.3	0.1	0.1	0.1	0.3	1.4				0.3				0.1	1.4		7.5
	S	S22																											
Power supply	G	S23	0.6	0.1				0.6	0.1			0.5	0.1			0.9	0.4		0.1		1.0	0.3				0.5			5.3
	M	S24	0.3	0.3	0.3			0.3	0.3	0.3	0.1	0.3	0.4	0.1	0.1	0.5	0.3	0.3			0.4	0.3	0.1		0.5		0.3		5.0
	C	S25	0.1	0.3	1.3			0.1	0.3	1.3	0.1	0.1	0.3	0.1	0.1	0.1	0.3	1.4				0.1	1.4			0.3			7.5
	S	S26																											
Total			9.9	4.9	7.1	1.4	1.5	9.3	3.9	6.9	3.9	7.5	7.5	2.0	3.9	10.9	6.0	7.9	2.6	1.3	5.1	4.5	7.5		5.3	5.0	7.5		133.0

Key: Low High

Figure 5. Aggregated linkage values between structural elements of the hairdryer

4.4 Discussion of numerical analysis

The result of this analysis is a matrix showing linkages between structural, behavioural, and functional elements of which only the linkages between the structural attributes are depicted above. Each linkage can be retraced to propagation paths in the FBS Linkage model. A comparison shows that the MDM with the calculated linkages is of higher density than the initial MDM. This is due to the paths of higher order which are not included in the initial MDM. As the FBS Linkage model of the hairdryer is mapped as non-directional, both MDMs are symmetric. Different aggregations of linkage values (e.g. per component, per attribute type, etc.) are possible to analyse change propagation and gain a deeper understanding of the product. For example, an aggregation of linkage values per component delivers a DSM with the same elements as the Change Prediction Method. However, the aggregated DSM is of higher density than the combined risk matrix calculated by Clarkson et al. [2004] for two reasons: First, the initial matrix on which the linkage calculations are based is of higher density than the direct risk matrix from Clarkson and colleagues because the FBS Linkage model is based on 'possibilistic' dependencies and is captured at a more detailed level. Second, the calculated linkage values above include behavioural and functional dependencies most of which are hidden for the structure-based Change Prediction Method. In practice, the 'possibilistic' links could be reduced by considering design freezes and tolerance margins. Furthermore, the standard linkage values of 1.0 could be replaced with more accurate change impacts and likelihoods. Consequently, the density of the linkage matrix would be reduced and its prediction quality further improved. Furthermore, the following insights can be gained from the results of Figure 5:

- The linkage values between structural elements of same type are high because of direct links between them. Linkage values between structural elements of different types are lower as they are determined by indirect layer-crossing paths only. These linkage values reveal hidden dependencies such as the paths between the casing geometry and the material of all components which result from the heat behaviour relations. They would remain hidden when analysing only the structural layer.
- The column or row sums which show a summation per attribute type suggest that the geometry and colour attributes are the most interlinked. While the geometry attributes have

indirect influences on other attribute types such as material, the colour attributes mainly influence each other. Overall, the casing geometry is the most interlinked attribute.

- A summation per component suggests that the casing is the most interlinked component.

5. Conclusions

This paper has presented a framework for integrated EC prediction and analysis composed of two building blocks interlinked by parameters: (1) the FBS approach for modelling of ECs in the product domain and (2) the ASM approach for modelling of ECs in the process domain. Subsequently, this paper has specified the first block into the FBS Linkage model, the first reported attempt at modelling change propagation on the FBS approach. The great benefit of this model is its multi-layered product representation which allows capturing of change propagation paths not only wihin but also across the layers. Such layer-crossing paths would remain hidden for single-layered approaches. The causal FBS network promotes a deeper understanding of why and how changes propagate within the product domain. Furthermore, this network incorporates product attributes in the structural layer which can be used as an interface for linking the product domain to the process domain. The application of the FBS Linkage model to a hairdryer has demonstrated its general feasibility and valuable results for change prediction and analysis. Its use in the context of the proposed framework for integrated EC prediction and analysis is threefold: It can be applied (1) during conceptual design, to optimise the product architecture by decoupling functions and minimising linkages, (2) during embodiment and detail design, to calculate change propagation between structural, behavioural, and functional elements and optimise the product robustness by well-directed setting of tolerance limits, and (3) during detail design and throughout the product lifecycle, to support decisions and implementation of ECs through causal integrated change prediction and analysis. Future work will elaborate the representation of EC processes and the integration of both domains into a FBSPT-MDM, where P represents the process step layer and T the design task layer.

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