A framework for redesign using FBS models and grammar adaptation

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Abstract: This paper describes a framework for redesign. Stylistic change in the form of rule modification is used to transform grammars to produce designs conforming to new requirements. The mechanism that enables this modification is based on the Function-Behaviour-Structure (FBS) model of design. The framework provides a formal mechanism for redesign and defines a means to generate and link structures with different behaviour and functions within the FBS model of design. Redesign of a wall illustrates this framework.

1. INTRODUCTION

Design often involves different disciplines, each forming a particular domain with its specific viewpoint on the design. For example, an architect and a structural engineer each have their own requirements and interpretations of the design. The architect may consider spatial configuration and leave the structural engineer to design the load bearing capabilities of the building elements.

An initial design created in one domain is usually subject to modification by another, as each domain has different requirements. In this context, *redesign* is considered as the process of modifying an existing design based on additional criteria from another domain. The current workable design is the starting point for the redesign process and additional requirements from dif-

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ferent domains will modify this initial design to conform to additional requirements.

This paper describes a formal framework for redesign. The representational foundation for this framework is based on feature grammars (Brown, McMahon et al., 1995). The concept of stylistic changes as defined by rule modifications (Knight, 1994), serves as a basis for replacing rules used in the derivations of the original design with one that produce designs conforming to new requirements. The mechanism that enables this replacement is based on the Function-Behaviour-Structure (FBS) model of design (Gero, Tham et al., 1992). The main concepts for the redesign framework are described in the sections following.

The framework process is illustrated with the redesign of a wall, loosely based on the EDM project's descriptions of panel and core walls (Eastman, Bond et al., 1991).

2. FEATURE GRAMMARS AND KNOWLEDGE BASES

We assume here that original designs are typically produced with a CAD tool such as a solid modeller. The design process can be carried out with native geometries or predefined feature sets. The only requirement is that the resulting model be interpretable using feature sets of a specified domain, as needed. Typically, features are represented as graphs in a solid model data structure to enable graph grammars to be used for automatic feature recognition (Pinilla, Finger et al., 1989; Chuang and Henderson, 1991).

A domain-specific knowledge base is used for creating a feature grammar based on the functional requirements of the design. This grammar is used to parse the original design to create a structure based on the rules in the grammar. Each rule of this grammar has associated descriptions that provide functional or behavioural information for the features used. The parsing process extracts feature information from the initial design model, allowing reconstruction of the initial design via a feature grammar with a set of functional or behavioural descriptions.

The same knowledge base is also used to generate a set of rules that defines the underlying requirements for that particular domain. Each of these rules has a similar functional or behavioural description associated with it.

3. FBS MODEL OF DESIGN

In the FBS (Function-Behaviour-Structure) framework of design knowledge, function defines *what* the artefact does, while structure specifies the component parts and their interconnections. Behaviour specifies *how* the structure of the artefact achieves the required function and acts as a link between function and structure.

This framework of design knowledge explicates the relationships between function, behaviour and structure of an artefact and facilitates explicit reasoning among them (Gero, Tham et al., 1992). The incorporation of behaviour breaks the rigid coupling between form (structure) and function, and "enhances the range of computational models" by providing "the opportunity to explore a wider variety of solution principles without prejudice to certain artefacts allowing for innovative new solutions" (Welch and Dixon, 1992). Only behaviours that contribute to the fulfilment of functions specific to a particular viewpoint are considered.

The relationships between function, behaviour and structure are described using dependency networks. These networks show explicitly the relational, computational and qualitative knowledge among function, behaviour and structure in a schematic form (Gero, Tham et al., 1992). Graphs can be used to represent the dependency network (Qian and Gero, 1996). Each node in the network represents either a function; behaviour; structure or their characterising variables and the link across nodes describes the dependency between them. *Figure 1* illustrates a sample FBS representation for a panel wall.

Previous work using FBS paradigms has focussed on the static representation of FBS descriptions and not on their generation. As we are interested in redesign, we consider dynamic descriptions and propose a methodology for constructing FBS descriptions.

4. DESIGN DESCRIPTIONS

A formal grammar can be used to generate a design with an associated FBS description. As the geometric representation of the design is generated using the transformation rules, its FBS description is created by a function that maps designs in the language of the grammar to descriptions from a predefined set. The description function is specified by defining a description for the initial geometric state in the design grammar and a corresponding mapping function, *g(i)* for each transformation rule *i* (Stiny, 1981).

In our work design descriptions are used to model the FBS characteristics of a design. The description function creates an FBS representation of the design as it is generated by the design grammar. This description is then used for the redesign of the original artefact based on new requirements for the FBS characteristics of the design.

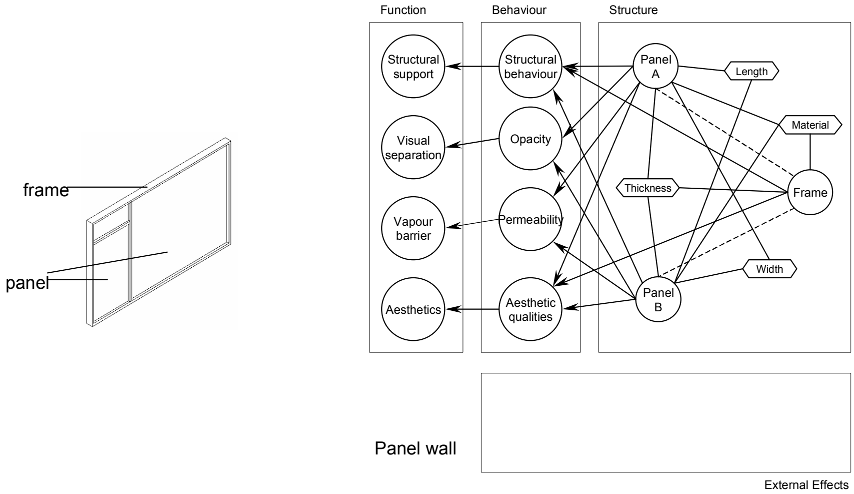

Figure 1. A panel wall and a corresponding FBS representation

5. STYLISTIC CHANGE AND GRAMMAR ADAPTATION

Terry Knight (1994) has demonstrated how systematic modification of shape grammars can encapsulate stylistic change. This occurs through addition, deletion or modification of grammar rules, often by shape replacement or modification of spatial relations. While capturing these changes in a very clear manner, there is little mention of the motivation for any transformation (admittedly a difficult thing to ascertain and decidedly outside the scope of her work).

In our work we expand the scope of these transformations to include ones based on modification of the functional, behavioural or structural characteristics of designs, as defined in their FBS descriptions. These transformations manifest themselves as rule replacements, and are motivated by specific requirements for redesign, e.g. new functional requirements.

6. REDESIGN FRAMEWORK

The redesign process is based on specific operations acting upon the functional, behavioural and structural properties of the original design within the context of additional requirements. An FBS description of the original design is first constructed and later modified. *Figure 2* illustrates the processes for this redesign framework, with explanation in the following sections.

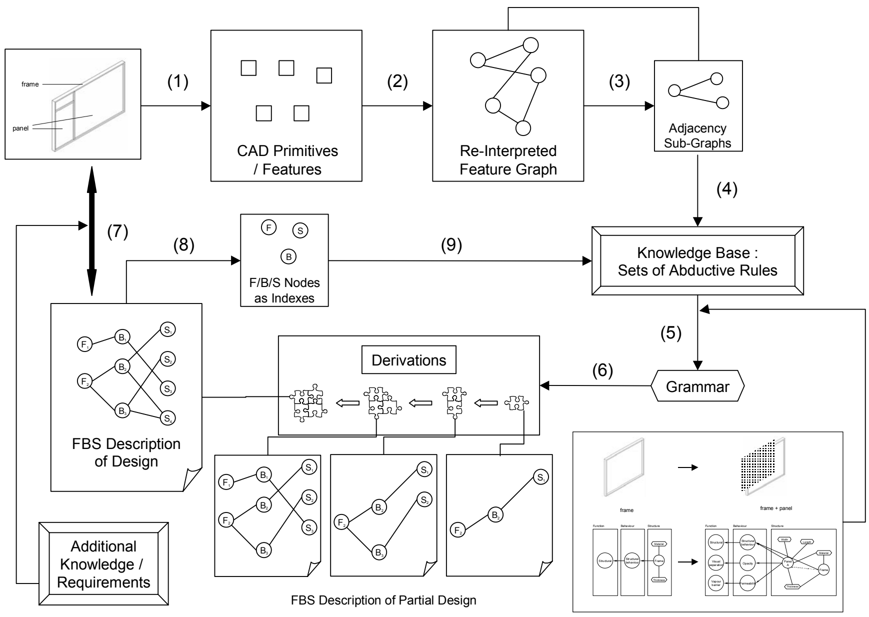

Figure 2. Construction of FBS description and the redesign process

6.1 Part I: Construction of FBS Descriptions

A design is created with a design tool such as a solid modeller by using its native geometries or predefined feature sets (1). The resulting model is reinterpreted as graphs of the required features specific to the relevant domain for redesigning (2). Typically, geometric features are represented as graphs of geometric entities in a solid model data structure and graph grammars can be used for domain-specific feature interpretation (Pinilla, Finger et al., 1989; Chuang and Henderson, 1991).

Adjacency sub-graphs of this feature graph are extracted (3) and used to search a knowledge base (4) for abductive rules that model part of the designer's knowledge (Gero and Maher, 1990). Each of these rules *R* is modelled with a mapping function *g(R)* that generates its FBS description. The structure part of this description contains adjacency information between physical elements that is matched against the adjacency sub-graphs from the original design for the retrieval of relevant rules. *Figure 3* illustrates an example of one such rule.

A grammar is assembled from a set of such rules (5) and then used to construct a derivation of the original design (6). This derivation recreates the original subassembly with an associated FBS description. This description is represented as graphs that define the various functional, behavioural and structural properties of the original design as nodes and their relationships as arcs. Additional input from the designer may be required to form a more complete FBS description, as the derivation only provides a partial description (7). This additional information can be obtained from a functional analysis of the original design.

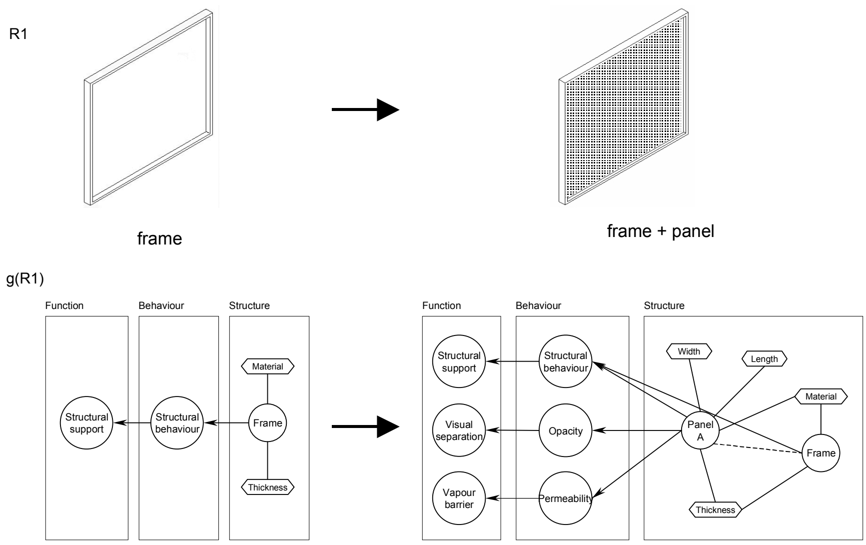

Figure 3. A sample abductive rule R1 with its associated function g(R1) to generate the FBS description of a panel wall

6.2 Part II: Redesign

To carry out redesigning, the various nodes in the FBS description of the original design are used as indexes (8) in the search for alternatives in the library of abductive rules (9). New rules are selected, based on modified or additional requirements for the functional, behavioural and structural properties of the original design. An example in the domain of Design for Assembly (DFA) might consider the use of alternative devices for fastening in place of bolts and nuts, based on a requirement of fewer parts. The function "fastening" would be used as an index to search for relevant rules containing the function "fastening" in their associated FBS descriptions.

The original rules in the grammar are replaced by the newly selected rules, resulting in the transformation or "adaptation" of the original grammar. A new design is regenerated using the adapted grammar and its corresponding FBS description is created. Comparing the original and modified FBS descriptions highlights potential requirements for any elements that are added or modified.

7. AN EXAMPLE: WALL REDESIGN

The following example illustrates an application of the framework described above in the context of redesigning a wall to satisfy additional performance requirements. It is loosely based on the representation of panel and core walls described in the EDM project (Eastman, Bond et al., 1991).

Here we assume that the user utilises features (wall and panel components) to design the wall assembly (*Figure 4*). Any feature recognition process can thus be ignored; the frame and panels form the features involved in the wall redesign.

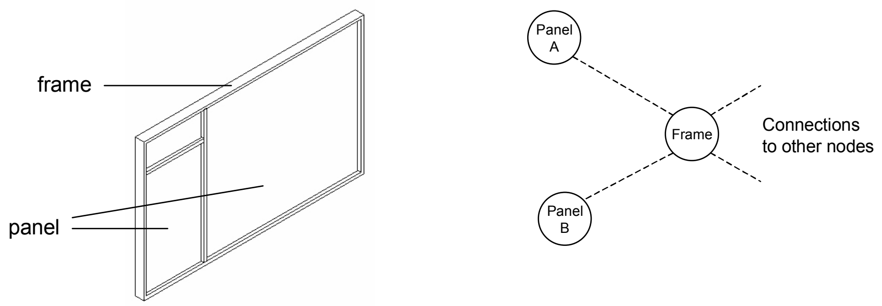

Figure 4. Panel wall and its adjacency graph

The adjacency between these features can be obtained from the CAD database of the original design. This adjacency sub-graph is used to search for rules in the knowledge base that have the same adjacency information in their FBS descriptions (e.g., match the panel-frame adjacency sub-graph on the right side of g(R1), *Figure 3* with a sub-graph of the one in *Figure 4*).

A grammar can be assembled from a set of such rules and then used to construct the derivations of the original wall assembly. This derivation generates the original wall with an associated FBS description. The description for the subassembly is illustrated in *Figure 1*. Note that the panel insertion rule provides only part of the FBS description. The function and behaviour dealing with aesthetic properties are obtained from the designer's knowledge base. Other such functions and behaviours could be added via a rigorous functional analysis, e.g. increased rigidity for the structural behaviour.

For redesign in the context of this example, the assumption is made that the acoustic and thermal properties of the proposed wall now become relevant, having previously not been considered in the FBS representation for the panel wall. These functions and behavioural requirements are added to the FBS description of the proposed wall (8) and the knowledge base is searched again for rules that contain these nodes (9). Rules such as those that construct core walls (R2, *Figure 5* and *Figure 6*) can be used to revise the grammar by replacing the analogous rules for panel walls. By replacing the rule invocations of R1 in the original derivation (6) with those of R2 and R3 (adding surfaces to core walls, not illustrated), a new core wall design is generated that satisfies the additional thermal and acoustical requirements. The original grammar has now been adapted to produce new designs according to a new set of requirements.

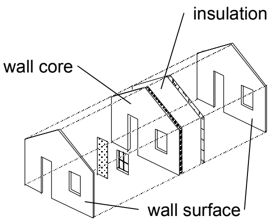

Figure 5. Core wall

The new design for the wall assembly is constructed from the derivations of the adapted grammar and its corresponding FBS description is generated. An understanding of the differences in the functional, behavioural and structural aspects of the original and modified designs can be obtained through a comparison of their FBS descriptions (*Figure 7*). Note that due to the additional functional requirements and the measured behaviours associated with them, the effect of external variables such as climate becomes relevant.

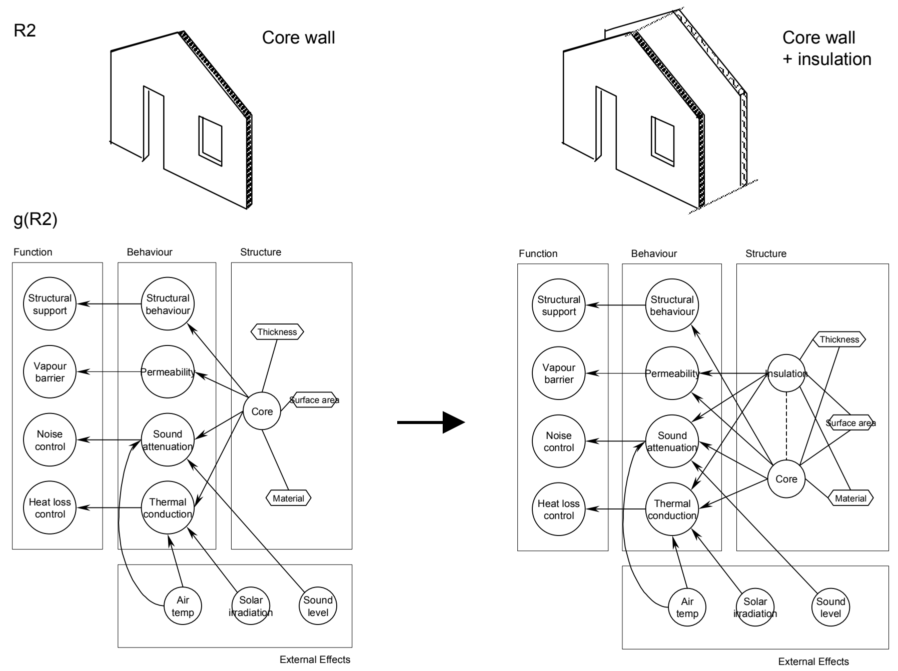

Figure 6. Rule R2 for core wall construction

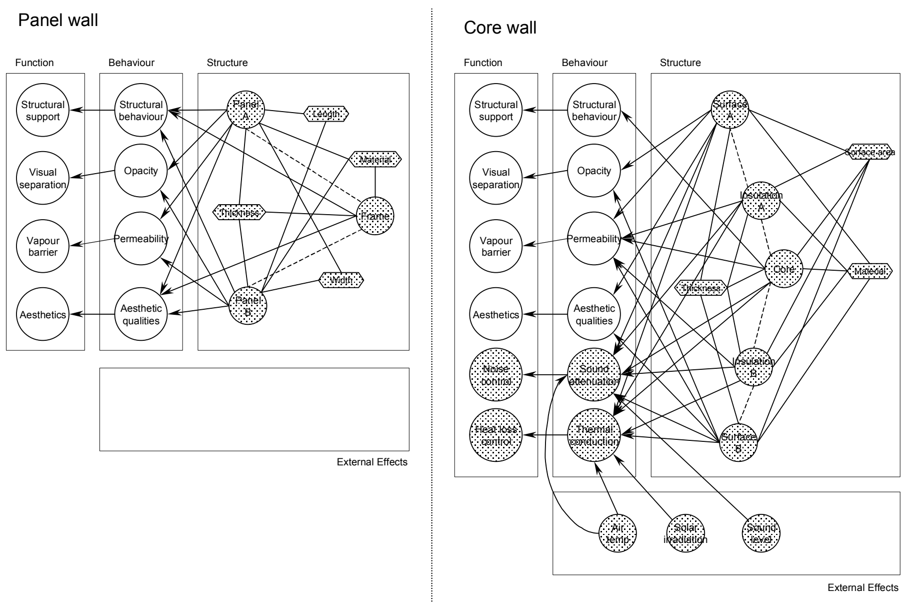

Figure 7. Comparison of the panel and core wall FBS descriptions. Differences are shaded.

In this example the introduction of new functional requirements (thermal and acoustic) resulted in the complete replacement of the original structure. Other possibilities for redesign could result in less drastic modification of the FBS network or a simple modification of the acceptable range for behavioural or structure variables. We also note that the introduction of new functions initiated the redesign process. In other situations, such as Design for Assembly, the requirement for fewer parts can lead to a partial modification of structure, but introducing new behaviours (e.g., the replacement of a nut and bolt fastener with a snap-fit adds the behaviour of elastic distortion).

8. FUTURE WORK

In this paper we have proposed a framework for redesign by grammar modification through rule replacement. Further work, including testing of this framework, is required. Additionally, other areas worthy of further investigation include:

- Use of the framework for more complex examples than the one illustrated here. How well will this methodology scale?
- Control of rule selection and invocation, especially in ambiguous, non-deterministic cases.
- Exploration of how prototype libraries can be used in redesign. For example, other possible paradigms used for redesign not examined here include combination, analogy and case-based reasoning.
- Formalisation of design principles by graph operations on FBS descriptions. One such domain could be Design for Manufacturing Assembly (DFMA), in which guiding principles include reduction of number of parts, combination of parts and simplification of designs.

9. SUMMARY AND CONCLUSIONS

In this paper we described a methodology for formalising redesign based on functional, behavioural and structure requirements. We proposed a process for the generation of FBS descriptions of designs based on adjacency graphs of their components and knowledge bases of component behaviour. By replacing the rules used to generate a design (adapting the grammar), new designs are created that meet new requirements. This framework has the potential to support the formalisation of engineering design methodologies such as DFMA.

10. ACKNOWLEDGEMENTS

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