

Feature Relations Graphs: A Visualisation Paradigm for Feature Constraints in Software Product Lines

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Abstract—Software Product Line Engineering is a mature approach enabling the derivation of product variants by assembling reusable assets. In this context, domain experts widely use Feature Models as the most accepted formalism for capturing commonality and variability in terms of *features*. Feature Models also describe the *constraints* in feature combinations. In industrial settings, domain experts often deal with Software Product Lines with high numbers of features and constraints. Furthermore, the set of features are often regrouped in different subsets that are overseen by different stakeholders in the process. Consequently, the management of the complexity of large Feature Models becomes challenging. In this paper we propose a dedicated interactive visualisation paradigm to help domain experts and stakeholders to manage the challenges in maintaining the constraints among features. We build Feature Relations Graphs (FRoGs) by mining existing product configurations. For each feature, we are able to display a FRoG which shows the impact, in terms of constraints, of the considered feature on all the other features. The objective is to help domain experts to 1) obtain a better understanding of feature constraints, 2) potentially refine the existing feature model by uncovering and formalizing missing constraints and 3) serve as a recommendation system, during the configuration of a new product, based on the tendencies found in existing configurations. The paper illustrates the visualisation paradigm with the industrial case study of Renault’s Electric Parking System Software Product Line.

I. INTRODUCTION

Modern software development often leads to software product variants that share a set of commonalities and differ in a few variability points. There is thus today a momentum for Software Product Line Engineering (SPLE) [24] as a suitable paradigm of software development for reducing both the maintenance effort and the time to market. In this context, practitioners and researchers alike, rely on Feature Models (FMs) [16], [25] as the main formalism for capturing commonality and variability of products in terms of *features*. A feature is defined as a prominent or distinctive and apparent aspect, quality, or characteristic of a system [16]. A given FM describes the set of valid combinations of features, referred to as configurations, for the system. Visually, the FM is often represented in a diagram, as illustrated by Figure 1 regarding a Car FM. The hierarchy of features includes mandatory features (*Gear*, *Car*), optional features (*DriveByWire*, *ForNorthAmerica*), alternative features (*Manual* or *Automatic*), and other potential constraints such as feature implications (*DriveByWire*

requires Automatic). Implications and mutual exclusions are referred to as *hard constraints* since no valid configuration can violate these constraints. However, there exists other constraints, known in the literature as *soft constraints* [9], whose violations do not lead to incorrect configurations. Such constraints are used during the configuration process of a new product to provide suggestions in feature selections. In the Car example, based on domain expert knowledge, selecting the *ForNorthAmerica* feature could suggest the selection of *Automatic* gear.

Real-world SPLs yield FMs that can be large and complex with thousands of features and as many constraints. As an example, researchers have already reported the challenges of dealing with the 8000 features of the Linux kernel [28]. In general, FM constraints are initially formalized by the different stakeholders at the domain engineering step. However, the evolution of the SPL could require modifying or adding features and new hard and soft constraints could appear requiring a refinement of the existing FM. Such large FMs present many issues for human comprehension. Apart from that, with such numbers of features and constraints it is possible to have *non formalized* constraints. Non formalized constraints are those that exist implicitly but that are not explicitly defined in the FM. Consequently, non formalized constraints could be the cause of potential invalid derived products. Extracting algorithmically the constraints of the FM can be useful to formally analyse the SPL and ensure that it is consistent with actual (i.e., already instantiated) and future configurations. Mining non formalized FM constraints from existing configurations is known however to be a challenging endeavour in the community of SPLE. A large body of literature is dedicated

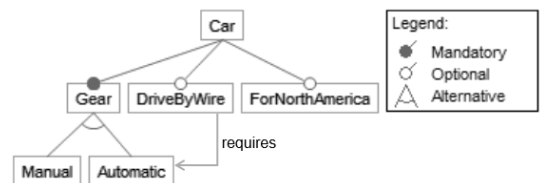


Fig. 1: Example of Car Feature Model. Credits to Czarnecki et al. [9]

to this issue. Most approaches [12], [15], [18], [19], [26], [31] target hard constraints, while others also propose algorithms to extract soft constraints [9]. Once constraints are mined, they must be confirmed by the different stakeholders. Unfortunately, from the domain expert perspective, enumerating and displaying hundreds of constraints will inevitably lead to a tedious investigation analysis. A promising alternative would be to provide a visualisation paradigm that is more intuitive than a textual listing, and also provides free exploration.

Visualization and interactive techniques are widely accepted to reduce the complexity of comprehension tasks [6]. We contribute in this paper with a new visualization paradigm for feature constraints, i.e., relations. We present our approach for building Feature Relations Graphs (FRoGs), and we present experimental results in an industrial case study.

A FRoG representation targets different stakeholders (e.g., domain experts, product developers, and users) and different usage scenarios (design analysis, documentation, and recommendation).

The main contributions of this paper are:

- We propose a new visualization paradigm to intuitively represent the relations among features in an SPL.
- We propose an approach for mining constraints from existing configurations to feed our visualization tool.
- We demonstrate the usability of our tool in different usage scenarios, based on a real-world dataset from a major manufacturer.

The remainder of this paper is structured as follows: Section II presents the background of managing constraints in SPLE to motivate our work. Section III formalizes the data abstractions and describes our proposed visualization paradigm. Section IV presents the case study. In Section V we discuss related work and Section VI concludes and presents future work.

II. BACKGROUND AND MOTIVATIONS

In practice, as discussed in the literature [16], [25], a FM may contain *hard constraints* that express strong dependencies between features. Following the Car example, we cannot have the *DriveByWire* feature without the *Automatic* gear feature. The explicit formalization of such constraints assures the assembling of valid feature combinations that will violate neither structural nor semantic dependencies of the product variant that has to be created. Therefore a given FM describes the set of valid combinations of features. Each combination, referred to as *configuration* corresponds to a specific product. Table I shows all the possible valid configurations of the Car example. Although *Gear* and *Car*, as shown in Figure 1, are also features of the Car example FM, they are not in Table I because they are mandatory features that do not represent variation points for the SPL.

FMs could be expressed as propositional formulas as presented in [1], [10]. The “inclusion” implication constraints are expressed with the *requires* statement and “exclusion” constructions are expressed with the *excludes* statement:

- *requires*: Example: $A \Rightarrow B$. Feature A requires the presence of feature B.
- *excludes*: Example: $A \Rightarrow \neg B$. Feature A excludes the presence of feature B.

In the illustrative FM of Figure 1, a mutual exclusion ($Automatic \Rightarrow \neg Manual$, $Manual \Rightarrow \neg Automatic$) is formalized through the *Alternative* construction. However, a domain expert can also add hard constraints explicitly between any features in the FM hierarchy as for example $DriveByWire \Rightarrow Automatic$. Notice also that, because of logic inference rules, we can have hard constraints that are not explicitly formalized but that exist because of the other formalized constraints. This relation type between features is called *inferred constraint*. For example $DriveByWire \Rightarrow \neg Manual$ is an inferred constraint.

The presence of two features in a given product configuration can also be qualified in terms of *suitability*. Such relations between features have also been explored in the literature. Bühne *et al.* [5] refer to them as *hints* and *hinders* relations. In the Pure::Variants commercial tool [3], the terms *encourage* and *discourage* are used in reference to the constraints in such relations. Czarnecki *et al.* [9] formally refer to them as two particular types of *soft constraints*, in the sense that their violation does not give raise to incorrect configurations. They exist with the objective of alerting the user, providing suggestions during the configuration process [9] or as a way to capture domain knowledge related to these trends. We will use the notation below for *soft constraints*:

- *encourages*: Example: $soft(A \Rightarrow B)$. Feature A encourages the presence of feature B.
- *discourages*: Example: $soft(A \Rightarrow \neg B)$. Feature A discourages the presence of feature B.

This way, a domain expert of the Car example could explicitly formalize the soft constraint $soft(ForNorthAmerica \Rightarrow Automatic)$ mentioned before to capture this SPL domain knowledge.

In addition to features, constraints and configurations, the FM has the particularity to be addressed by different stakeholders at the same time. Indeed, and as mentioned by Yu *et al.* [32], variability in FMs arises from different stakeholders goals. Each stakeholder can thus be interested in a partial view of the variability included in a FM. In other words, each stakeholder has its own *stakeholder perspective*. For instance, features concerning the type of *Gear* in the Car example is mainly useful for final customers to choose their cars. However, *DriveByWire* is more the concern of engineers

TABLE I: Valid Configurations for the Car example.

| | Manual f_1 | Automatic f_2 | DriveByWire f_3 | ForNorthAmerica f_4 |
|--------|-----------------|--------------------|----------------------|--------------------------|
| Conf 1 | | ✓ | | ✓ |
| Conf 2 | ✓ | | | |
| Conf 3 | | ✓ | | |
| Conf 4 | ✓ | | | ✓ |
| Conf 5 | | ✓ | ✓ | ✓ |
| Conf 6 | | ✓ | ✓ | |

during the construction of the cars, while the *ForNorthAmerica* feature can be related to commercials and sales analysts. Each stakeholder perspective cannot ignore the impact of other features from other stakeholders perspectives. Consequently, fluent communication means should exist to reason about these feature relations that involves different stakeholders, called inter-stakeholder perspectives constraints hereafter.

As reported by [21], “*the use of visualisation techniques in Software Product Line can radically help stakeholders in supporting essential work tasks and in enhancing their understanding of large and complex product lines*”. In this paper, we face the visualisation of *feature constraints* using an innovative visualisation paradigm for the SPL community called FROGs. FROGs has three objectives:

- 1) Domain experts can rely on a FROG for a better understanding of relations among features. Potentially, it could help refining an existing FM by formalizing hard and soft constraints.
- 2) A FROG can also be used to document, at the domain level, each feature. Thus, stakeholders can visualize, in an interactive way, the relations among the features he/she is responsible for and others.
- 3) Finally, the representations of FROGs can be used to improve recommendation systems during product configuration. Indeed a FROG can better visually “explain” why two features should be selected together in comparison with another pair of features.

III. FROM CONFIGURATIONS TO FROGS

Before presenting the visualisation decisions, in subsection A we present the data abstractions used to build the FROG visualisation. Then, in subsection B we present how this data is displayed to fulfil the FROGs objectives and the existing interaction functionalities.

A. SPL data abstraction for FROGs

A configuration is defined as a set of selected features $c_i = \{f_1, f_2, \dots, f_n\}$. Let $VC = \{c_1, c_2, \dots, c_m\}$ be the set of all the possible valid configurations for a given FM. The number of valid configurations could be up to 2^n so there is a combinatorial explosion of valid feature combinations. SPLs normally have a subset of configurations from where the actual product variants are derived. Let $EC \subseteq VC$ be the set of existing configurations for an SPL. Our approach has the assumption that EC s are valid. Also, if duplicated configurations exist, our approach does not take them into account. Indeed, one configuration represents one product variant independently of the amount of units of the product variant that were derived. In the Car example, Table I presents the VC set. Let us consider that EC contains all VC excluding the last configuration *Conf6*. In this case EC is expressed as:

$$EC = \left\{ \begin{array}{l} c_1 = \{ \quad f_2, \quad f_4 \}, \\ c_2 = \{ f_1, \quad \quad \quad \}, \\ c_3 = \{ \quad f_2, \quad \quad \quad \}, \\ c_4 = \{ f_1, \quad \quad f_4 \}, \\ c_5 = \{ \quad f_2, \quad f_3, \quad f_4 \} \end{array} \right\}$$

Given this definition of EC , we can reason on the feature relations in this set. Let $EC_{f_i} = \{c \in EC : f_i \in c\}$ be the subset of existing configurations that contain the feature f_i . For example, the set of existing configurations that have the *Manual* feature is defined as $EC_{f_1} = \{c_2, c_4\}$. With this definition of EC_{f_i} , we can calculate the *proportion* of the apparition of a feature given the apparition of another feature. Following existing notation [9] we will call this operation $f_i \text{ given } f_j$. Equation 1 presents how this proportion is calculated. The formula is similar to the conditional probability formula but we use the term *proportion* instead of *probability* since probability is a hypothetical property while proportions summarize observations as it is the case when mining existing configurations.

$$f_i \text{ given } f_j = \frac{|EC_{f_i} \cap EC_{f_j}|}{|EC_{f_j}|} \quad (1)$$

In the Car example, the proportion of *Automatic* given *DriveByWire* ($f_2 \text{ given } f_3$) is 1 as when we have *DriveByWire* in the EC , we always have *Automatic*. In the same way, *Manual* given *Automatic* ($f_1 \text{ given } f_2$) is 0 as when we have *Automatic* we never have *Manual*. With the same formula, the proportion of *Automatic* given *ForNorthAmerica* ($f_2 \text{ given } f_4$) is 0.67. These proportions, that are continuous values from 0 to 1, are mapped to the different potential hard and soft constraints in the following way:

requires ($f_i \Rightarrow f_j$) when
 $f_j \text{ given } f_i = 1$
excludes ($f_i \Rightarrow \neg f_j$) when
 $f_j \text{ given } f_i = 0$
encourages ($\text{soft}(f_i \Rightarrow f_j)$) when
 $enc_{threshold} \leq f_j \text{ given } f_i < 1$
discourages ($\text{soft}(f_i \Rightarrow \neg f_j)$) when
 $0 < f_j \text{ given } f_i \leq dis_{threshold}$

The thresholds $enc_{threshold}$ and $dis_{threshold}$ are defined and adjusted by domain experts based on their experience. These thresholds are also discussed and set by domain experts in the case reported at [9].

Regarding the stakeholder perspectives, each of them consists in the subset of features that are “owned” by a stakeholder. These subsets must be disjoint in the current version.

Finally, we define a confidence metric of the validity of the mined hard or soft constraints. The confidence metric is only applicable for relations that are not explicitly formalized in the FM. We consider that the ones already formalized are correct until modified or removed. In the case of non formalized hard constraints, the confidence metric, represents the probability of finding one configuration that violates this hard constraint.

If we have a constraint, for example $f_i \Rightarrow f_j$, the confidence of $f_j \text{ given } f_i$ is calculated as the percentage of the possible valid configurations containing f_i that exists in EC . Let $VC_{f_i} = \{c \in VC : f_i \in c\}$ be the subset of the valid configurations that contains the feature f_i . Equation 2 shows how the confidence metric, that only depends on f_i , is calculated.

The confidence will be increased when new configurations containing f_i are created reaching 1 when $EC_{f_i} = VC_{f_i}$.

$$Confidence(f_i) = \frac{|EC_{f_i}|}{|VC_{f_i}|} \quad (2)$$

In practice, the creation of the set VC_{f_i} is not needed to compute its cardinality. Calculating the number of valid configurations is a well known problem solved by existing FM automated analysis approaches [2] where the idea is to calculate the cardinality of $|VC_{f_i}|$ reasoning on the formalized constraints.

B. FROGs: Feature Relations Graphs

Our visualisation paradigm, called FROGs, has as objective to visualise the constraints (relations) between features based on the analysis of current configurations. Each FROG is associated with a specific feature to show how this feature is related, in term of hard and soft constraints, to the other features. A FROG is presented as a circle where the considered feature is displayed in the center¹. This feature in the center will be called f_c hereafter. All the rest of features that represent variation points of the FM are displayed around f_c with a constant separation of $\frac{2\pi}{|features|-1}$. This separation allows to distribute uniformly all the features around the circle. These features are ordered by stakeholder perspectives so we will have circular sectors for each of the stakeholder perspectives.

Before going into the details of the visualisation, Figure 2 shows the FROG of the *Manual* feature of the Car example. We can see *Manual* as f_c in the center and the rest of the features separated with a constant angle. We can see also the sectors of the different stakeholders mentioned in the introduction.

¹FROGs acronym is inspired by the metaphor that FROG graphs have water lily pond plant shapes and that the domain expert could navigate from one to another

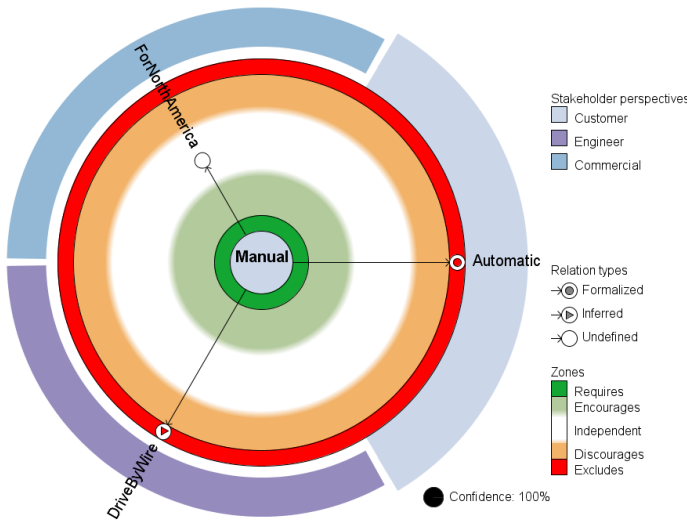


Fig. 2: FROG for the Manual feature of the Car example

1) *FROG's zones*: Each FROG displays five zones each of them associated with a specific color and related to a specific type of constraints. Figure 3 shows these zones and how the distance between the f_c and the boundary of the circle is calculated according to the f_i given f_c operation.

- *Requires Zone*. The Requires zone is reserved to the value 1 and it is the closest to f_c . Features in the Requires zone are “glued” to f_c meaning that if we have f_c then in all *EC* we have f_i . The Requires Zone and the Excludes zone are reserved to only one value and their size fits exactly with the diameter of the f_i nodes. The Requires zone is displayed with the green color.
- *Excludes Zone*. This zone, displayed with the red color, is in the extreme of the circle and therefore is the farthest from the f_c to illustrate that f_c and f_i were not together in any configuration.
- *Encourages Zone*. This zone includes all f_i that are potentially encouraged by the presence of f_c . The color is a pale green meaning that it is close to the Requires zone but without reaching it. The Encourages zone fades to white in the Independent Zone at the distance defined by the $enc_{threshold}$.
- *Discourages Zone*. This zone includes all f_i that are potentially discouraged by the presence of f_c . The color is orange meaning that it is close to the Exclude zone but without reaching it. The Discourage zone fades to white in the Independent Zone at the distance defined by the $dis_{threshold}$.
- *Independent Zone*. This zone, located between the $enc_{threshold}$ and the $dis_{threshold}$, is displayed with the white color containing the features that are not impacted by the presence of f_c .

In the FROG of Figure 2 we can see how both *Automatic* and *DriveByWire* are in the Excludes zone and *ForNorthAmerica* (with a f_i given f_c of 0.5) is located exactly in the middle between the Requires and Excludes zones corresponding to the Independent zone.

The usage of colors in visualisation is an important design decision [27]. FROG zones depends to univariate data (f_i given f_c). This data has continuous values but, as we have shown, these values are mapped to zones in a discrete fashion. Therefore, we have defined boundaries and we associate one color to each of the zones following the color scheme shown in Figure 3.

The green of the Requires zone contrasts heavily with the red of the Excludes zone. The separation principle, that claims

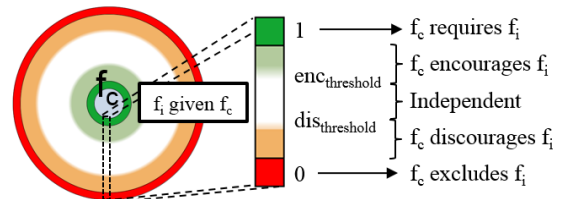


Fig. 3: FROG's zones

that close values must be represented by colors perceived to be closer, is respected with the green and the pale green for the Requires and Encourages zones as well as with the red and the orange colors for the Excludes and Discourage zones. The color scheme used in FROG’s zones can be seen as a diverging color scheme given that it illustrates the progression from a central point.

Colder colors are perceived to be lower than warmer colors as in the case of heat maps. This is respected in FROGs taking into account that the distance from f_c to the Requires zone is lower than the higher distance to the Excludes zone. In addition, as it happens with the traffic lights metaphor shared by most of the cultural contexts, the red color for the Excludes zone has a connotation of interdiction while the green of the Requires zone has a connotation of being positive.

The size of the Requires and Excludes zones fits exactly with the size of a f_i node while the other zone sizes depend on the percentage defined in the $enC_{threshold}$ and $dis_{threshold}$. The fade from the Encourages and Discourages zones is very small in size and it is aimed only to create a visual effect that these boundaries are not as restrictive as the hard constraints boundaries represented with a black line. For example, a feature f_i with a formalized excludes hard constraint cannot appear in the discourages zone because otherwise it was not a hard constraint. On the contrary, one feature f_i that has not a hard constraint could “move” between the Encourages, Independent and Discourages zone over time because of the addition of new configurations.

2) *Formalized and non formalized constraints*: A FROG displays the mined constraints by analysing the EC . However, some of them (or all in an optimistic case) are normally already defined in the FM. In the FROG visualisation, for these already formalized constraints we add a circle in the node of f_i with the color of the corresponding constraint’s type as shown in Figure 4. For example, $Manual \Rightarrow \neg Automatic$ is an already formalized constraint and Figure 2 shows this notation on the *Automatic* node with the red color as it is an Excludes constraint.

Notice that, if we have formalized soft constraints, it could happen that the mining process on EC may situate f_i in a FROG zone that does not correspond to the defined soft constraint. This could alert the user about a general violation of the formalized soft constraint.

Figure 2 shows the FROG legend at the right side of the image. In this legend, the “Relation types” category shows the notation for other types of feature relations apart from the Formalized relation. We use the grey color in the figures but





-  Formalized Requires constraint
-  Formalized Excludes constraint
-  Formalized Encourages constraint
-  Formalized Discourages constraint

Fig. 4: Formalized constraints notation

it will be the color of the different constraints and, in any case, grey color. An inferred constraint, as explained before, is a constraint that is not formalized in the FM but that exists because of logical rules. Figure 2 shows an example of it in the *DriveByWire* node. We use the triangle to differentiate it from the circle of the formalized constraints. The triangle metaphor contrasts with the circle and it has the connotation of an arrowhead representing the existence of a rule of inference. If it is neither a formalized nor inferred constraint, we will refer to it as an undefined relation independently of the zone where the f_i is placed. Undefined relations do not contain any symbol inside the f_i node.

3) *Stakeholder Perspectives*: Each stakeholder perspective has an associated color that is used in the circular sectors of the FROG. The f_c node has the color of the stakeholder perspective it belongs to, and also, this circular sector has a slightly bigger radius. Figure 2 shows how the *Manual* feature has the *Customer* color and that the *Customer* sector has bigger radius.

The stakeholder perspectives colors could be changed by users but default colors are provided. Stakeholder perspectives are nominal data and we used a qualitative color scale that does not imply order. Figure 5 shows the used color scheme. In the rejected alternatives section III-E2, it is discussed why only grey, purple and blue variations are present in this default color scheme.



Fig. 5: Default color scheme for the nominal data of stakeholder perspectives

4) *Displaying the Confidence*: The confidence is displayed outside of the circle as a percentage accompanied by a pie chart visualizing this percentage. In Figure 2 we can see in the bottom-right side a Confidence of 100% and complete black circle. As another example Figure 6 shows the visualisation of the confidence with a value of 5%.

C. Interaction possibilities

FROGs was implemented as a visualisation tool allowing free exploration. The navigation and filter capabilities are discussed in the next paragraphs. To illustrate these interaction possibilities, Figure 6 shows a screen-shot of FROGs visualisation tool at which we added dashed sections to differentiate the different parts. The “Name of the FM” part just shows the name of the FM of the SPL while the “Feature List” part contains all the variable features of this FM. The “FROG” part shows the FROG of the selected feature with the “Confidence” and “Legend” sub parts. Finally, the “Actions” part activates different interaction capabilities.

1) *Navigation*: On the left side of Figure 6 we can see the “Feature List” part. A bold font and an arrow is used to distinguish the selected feature. We can click in any feature or use the keyboard to change the displayed FROG. We can also click in any node of the graph to navigate to the FROG of the selected feature.

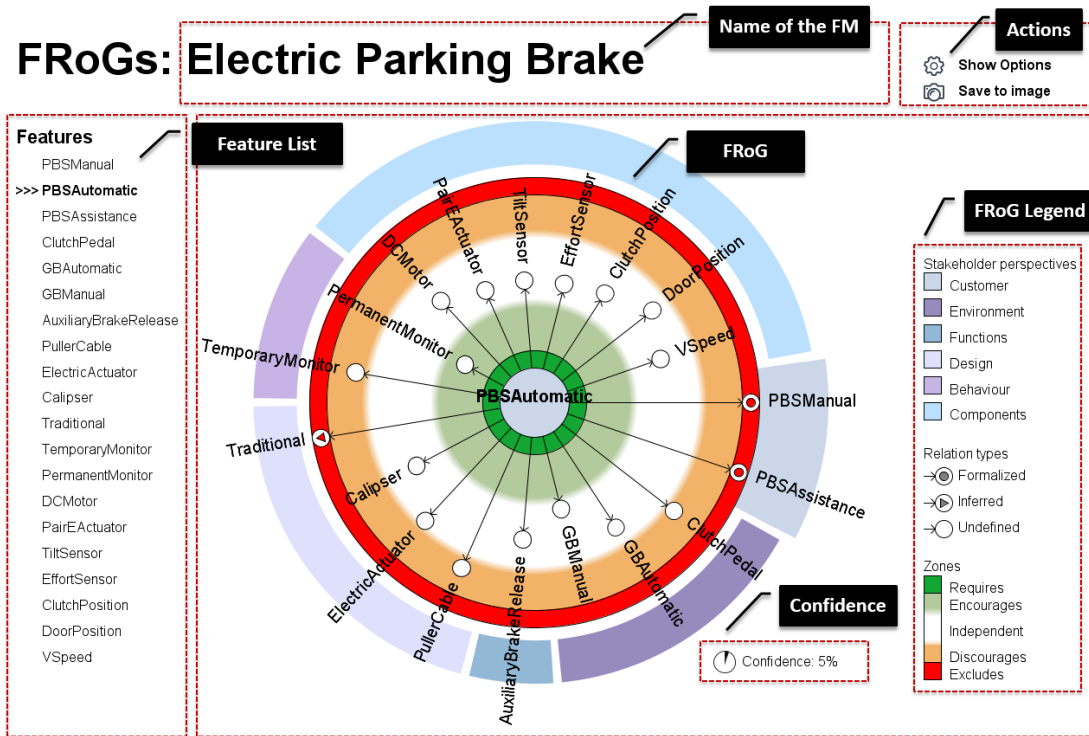


Fig. 6: Screenshot of FROGs visualisation tool focusing on the PBSAutomatic feature of the Electric Parking Brake SPL

2) *Filters*: Filters can be applied simultaneously to hide feature nodes of stakeholder perspectives, relation types or FROG zones. FROG users should click on the “Show Options” button of the “Actions” part to have access to these functionalities. By clicking this button, checkboxes will appear on the FROG legend to activate or deactivate the filters as shown in Figure 7. The button “Show Options” text changes to “Hide Options” to hide these functionalities and come back to the purely visualisation operations.

Different filter combinations could fulfil different objectives of FROGs usage as for example:

- *Documenting constraints*: We focus on constraints by hiding all features on the Independent zone.
- *Discovery of non formalized constraints*: We focus on potential constraints by hiding all features on the Independent zone and those constraints that are already formalized or inferred.
- *Intra-stakeholder perspectives constraints*: We hide all the features that do not correspond to a given stakeholder perspective.
- *Inter-stakeholder perspectives constraints*: We hide all the features that do not correspond to a given set of stakeholder perspectives.

3) *Adjusting encourages and discourages thresholds*: By clicking in the “Show Options”, apart from the filtering checkboxes, the legend of the zones is transformed in a range slider. Figure 6 shows the initial appearance of the legend of the zones at the bottom of the “Frog Legend” part, and Figure 7 shows the legend of the zones enriched with the

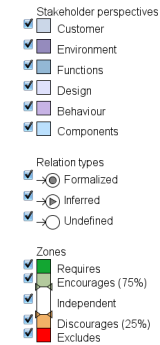


Fig. 7: Filtering options and slider for adjusting encourages and discourages thresholds

slider functionality and with a textual representation of the selected percentages. Using this slider, the $enc_{threshold}$ and $dis_{threshold}$ could be adjusted at will. Interacting with the slider provides automatic feedback in the FROG by changing the size of the zone. If filters are applied to the feature nodes, these filters have also effect so hidden nodes could appear or disappear while interacting with the slider.

4) *Save as image*: Another interaction capability of the visualisation tool is a button to save the current FROG (filtered or not filtered) and the legend to an image file. This functionality is available in the “Actions” part of Figure 6. The “Name of the FM”, “Actions” and “Feature List” parts are not appearing in the saved image and therefore it can be used directly for documentation or to illustrate some phenomena in feature relations.

D. Time response

FROGs was implemented with Processing 2.0 [8] and we achieve complete visual continuity. $f_i \text{ given } f_j$ is an algorithm with order $\mathcal{O}(m)$ where m is the number of existing configurations. Therefore, displaying a FROG is $\mathcal{O}(nm)$ being n the number of features. The number of possible valid configurations is precomputed before starting the visualisation. The needed set of input files for FROG are exported using the SPL tool Feature IDE [29] and the mapping from stakeholder perspectives to features are defined in another configuration file.

E. Rejected alternatives

1) *Colors of Requires and Excludes zones*: In the beginning we used pale green and pale red for the Requires and Excludes zones but users reported that they will prefer more intense green and red colors for these zones to catch more attention on hard constraints.

2) *Default colors for stakeholder perspectives*: Qualitative scales for nominal data are publicly available as for example the color scheme provided by ColorBrewer 2.0 [7] shown in Figure 8. We started using this color scheme but users complained about the similarities between some of the colors of the stakeholder perspectives' sectors and the red of the Excludes zone. For instance, the fourth color of Figure 8 was a cause of confusion. We decided to exclude those colors that were similar to red, orange as well as similar to green and pale green.

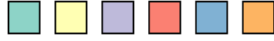


Fig. 8: Rejected default color scheme for the nominal data of stakeholder perspectives

3) *Relation types*: The current version of FROGs only has the possibility to see the impact of the presence of f_c in the presence of the other features f_i . In order to display other phenomena in the relations of a given feature f_c , FROGs implementation was flexible to show the impact of the presence or absence of f_c in the presence or absence of other features f_i . It was also available to show the impact of the presence or absence of the rest of the features f_i in relation with f_c . These aspects give raise to eight possible FROGs for a given f_c from which Figure 9 shows four of them that could be obtained from a given f_c .

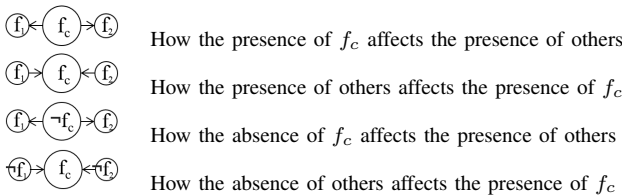


Fig. 9: Different relations regarding presence or absence of features, and the direction of the relation regarding the FROG central feature

The other four combinations could also be displayed even if they are the “inverse” of one of these four types because of the following property of the $f_i \text{ given } f_j$ operation: $f_i \text{ given } f_c = 1 - (\neg f_i) \text{ given } f_c$. Notice that the direction of the arrows from f_c to f_i changes in types one and two, and three and four. To obtain the distances in the cases that we want to show the impact of other features on f_c , it is enough to inverse the $f_i \text{ given } f_j$ operation: For type one is $f_i \text{ given } f_c$ while for type two is $f_c \text{ given } f_i$.

This functionality in the options of the visualisation tool gave raise to many confusion in the users. It is not easy to think about presence and absence of features in combination with the direction of the arrows. Our case study did not need these kinds of relation visualisation for documentation nor for constraint discovery so we decided to remove it for easing FROGs usage until we prove its usefulness in some scenario. Current version of FROGs visualisation corresponds to the first type of Figure 9 as shown for example in Figure 2.

IV. CASE STUDY AND DISCUSSIONS

In the previous sections we illustrated FROGs on the Car example. In this section we present FROGs evaluation on an industrial case study in the automotive industry concerning the Renault’s Electric Parking Brake (EPB) SPL [13], [20]. First we describe the case study and then we discuss the results.

A. Case Study: Electric Parking Brake

The EPB system is a variation of the classical, purely mechanical, parking brake, which ensures vehicle immobilization when the driver brings the vehicle to a full stop and leaves the vehicle. The case study is focused on the variability in the BOM (Bill of Materials) related to the logical/physical components of the EPB. Figure 10 presents the FM specified by domain experts. This FM contains 20 variable features and 32 hard constraints. In concrete, the *Alternative* constructions between features define 24 hard constraints and 8 are expressed as logical expressions. The possible valid configurations of this FM are 2976 while the existing configurations that were provided are 200.

The variability in this SPL is described by Renault according to six stakeholder perspectives that represent different subdomains of the EPB’s variability. These stakeholder perspectives are *Customer*, *Environment*, *Functions*, *Design*, *Behavior* and *Components*. We present here a brief description of these perspectives and their associated features.

a) *Customer*: Customer visible variability is handled by the product division. For customers, the parking brake proposes three types of services: The manual brake is controlled by the driver either through the classical lever or a switch; the automatic brake is a system that may enable or disable the brake itself depending on an automatic analysis of the situation; the assisted brake comes with extra functions which aid the driver in other situations such as assistance when starting the car on a slope. The features concerned by this perspective are thus *PBSManual*, *PBSAutomatic* and *PBSAssisted*.

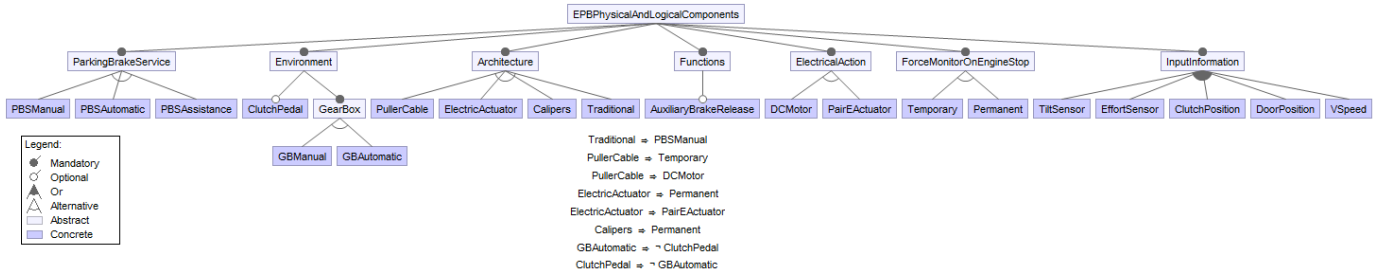


Fig. 10: Electric Parking Brake system Feature Model for physical and logical components

b) *Environment*: For vehicle environment, the variability concerns the Gear Box where we distinguish two possible variants: *GBManual* and *GBAutomatic*. The presence of a *ClutchPedal* is also an optional feature.

c) *Functions*: The feature *AuxiliaryBrakeRelease* is related to an optional function of the system that includes an auxiliary brake release mechanism.

d) *Design*: There are different alternatives that concern design decisions of the EPB. These design decisions impact the whole or parts of the technical solution. For architectural design, there are four feature alternatives: *PullerCable*, *ElectricActuator*, *Calipser* and *TraditionalPB*.

e) *Behavior*: Braking pressure is monitored after the vehicle has stopped for a certain amount of time for the single DC motor or permanently monitored for other solutions. The Behaviour includes thus the features *TemporaryMonitor* and *PermanentMonitor*.

f) *Components*: The variability in the EPB also concerns the physical architecture/components. This consists in the presence of different means of applying the brake force: electric actuators mounted on the calipers or single DC motor and puller cable much like the traditional mechanical parking brake. Also the type of sensors available may vary depending on the configuration and needs. This perspective thus includes the following features: *DCMotor*, *PairEActuator*, *TiltSensor*, *EffortSensor*, *ClutchPosition*, *DoorPosition*, and *VSpeed*.

B. Results: FRoGs of the Case Study

From the 200 existing configurations of the EPB case study we obtained 20 FRoGs, one per feature. Figure 6 shows these features in the “Feature List” part. Table II shows the information that can be visualised on the FRoG of each feature. For each FRoG’s central feature, the table shows the number of constraints that can be identified by analysing the different zones. Regarding the soft constraints, the values used for $enc_{threshold}$ and $dis_{threshold}$ are 25% and 75% respectively. Figure 6 shows the *PBSManual* FRoG, that corresponds to the second element in Table II, where we can see that it displays 2 hard constraints, 1 inferred, and 4 potential soft constraints.

Before experimenting with domain experts, we manually checked the correctness of the visualised information. Concretely, we checked manually that the formalized hard and inferred constraints of the FM appear in the displayed FRoGs.

TABLE II: Number of the identified constraints using FRoGs

| FRoG central feature | Hard | Inferred | Soft |
|---------------------------|-------------|-------------|-------------|
| PBSManual | 2 | 0 | 2 |
| PBSAutomatic | 2 | 1 | 4 |
| PBSAssistance | 2 | 1 | 3 |
| ClutchPedal | 1 | 1 | 4 |
| GBAutomatic | 2 | 0 | 4 |
| GBManual | 1 | 0 | 4 |
| AuxiliaryBrakeRelease | 0 | 0 | 4 |
| PullerCable | 5 | 2 | 0 |
| ElectricActuator | 5 | 2 | 0 |
| Calipser | 4 | 1 | 0 |
| Traditional | 4 | 2 | 0 |
| TemporaryMonitor | 1 | 2 | 2 |
| PermanentMonitor | 1 | 1 | 1 |
| DCMotor | 1 | 1 | 3 |
| PairEActuator | 1 | 1 | 3 |
| TiltSensor | 0 | 0 | 5 |
| EffortSensor | 0 | 0 | 4 |
| ClutchPosition | 0 | 0 | 4 |
| DoorPosition | 0 | 0 | 4 |
| VSpeed | 0 | 0 | 4 |
| Total | 32 | 15 | 55 |
| Average | 1.6 | 0.75 | 2.75 |
| Standard Deviation | 1.67 | 0.79 | 1.68 |

We discuss now some analysis that domain experts made using FRoGs and how it helps in the comprehension of feature relations in the EPB SPL. For instance, analysing the FRoG associated with the *EffortSensor* feature (see Figure 11), it is observed that it has no hard constraints to any other features. That means that it has no hard impact on the presence or absence of any feature. However, the feature *PullerCable* (see Figure 12) has a great impact on other features as the *PullerCable* FRoG shows seven features on the Excludes and Requires zones.

No undefined hard constraints were found neither in the Excludes nor Requires zones in EPB’s FRoGs. However, thanks to FRoGs, as shown in Table II, 55 potential soft constraints are displayed. By visualising this, domain experts are able to think about two possibilities: a) whether it is an actual soft constraint that should be formalized or b) FRoG displayed a fact based on the existing configurations but it is not an actual soft constraint. The exercise also enables to think about the thresholds for the Encourages and Discourages zones.

The FRoGs for the EPB’s FM also represented a visualisation paradigm to understand the relations between stakeholder perspectives. From the 47 hard or inferred constraints, 20 of them are hard constraints that relate features belonging to

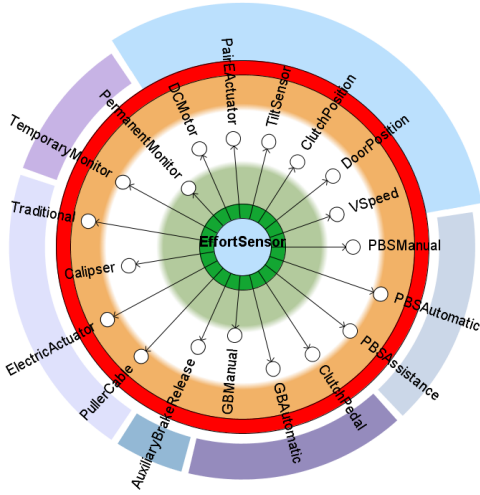


Fig. 11: FRoG of *EffortSensor* feature without filters showing that it does not representatively affect other features

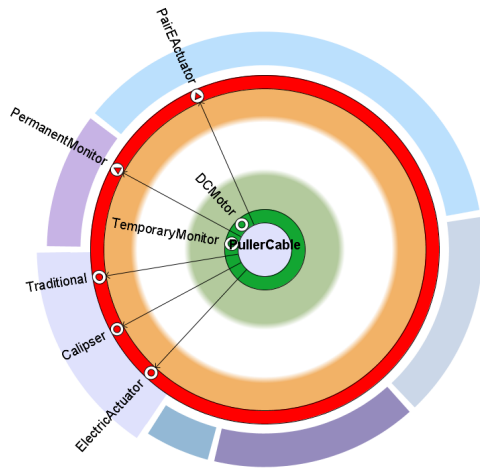


Fig. 12: FRoG of *PullerCable* feature with a filter hiding Independent zone features to illustrate great impact on other features

different stakeholder perspectives. Figure 12 shows 4 inter-stakeholder perspectives hard constraints: *TemporaryMonitor*, *PermanentMonitor*, *DCMotor* and *PairEActuator*. In addition, in the case of soft constraints, the 55 soft constraints are between inter-stakeholder perspectives. Figure 11 shows 4 of them: *PullerCable*, *ElectricActuator*, *PermanentMonitor* and *PBSAutomatic*.

V. RELATED WORK

As presented above, the FM is classically visualised as a tree structure consisting of features. Constraints between these features are displayed using the Alternative and the Or variability notation. Constraints (e.g.; requires, excludes) can also be explicitly formalized textually (Figure 10) as logical expressions or graphically (Figure 1) as arrows between features [16], [25]. As discussed in this paper, real-world SPLs yield FMs that can be large and complex with many

constraints. Hence, it is difficult to use this representation to help domain experts to understand relations between features. In recent years, the use of visualisation techniques in the SPL community has received a lot of attention proposing new alternatives to visualise FMs. Trinidad *et al.* [30] proposed the cone tree visualisation paradigm introducing a 3D representation of FMs. However, this visualisation is only proposed to represent the hierarchical information included in large FM and the authors do not consider constraint visualisation.

SPL visualisation related work mainly consider the use of visualisation techniques to help domain experts for *product configuration*. Product configuration is the process that consists in selecting, from the FM, the list of features that will be included in the target configuration. Visualisation is often combined with interactive techniques to support product configuration. A survey on the use of visualisation techniques for product configuration is presented in [23]. Nestor *et al.* [21] propose a tool called VISIT-FC (Visual and Interactive Tool for Feature Configuration) that introduces visualisation techniques to address product configuration. For constraint visualisation, this tool only uses arcs between features. Constraints are also visualised as arcs in the S2T2 visualisation tool [22]. [4] also discuss product configuration but without considering constraint visualisation. In [17], the authors propose the use of visualisation techniques to display features for pairwise testing but constraints are not visualised. On the contrary, we propose FRoGs as a new formalism to visualise constraints between features. Instead of classical representations where constraints are integrated in FMs and often visualised as arcs between features, FRoGs display the constraints focusing on relations of each feature with the rest of the features. This allows to study the impact of each feature on the rest of the FM. At our best knowledge FRoGs represent the first work in this direction.

In Section III, we presented our approach to extract constraints and build FRoGs from existing configurations. Extracting constraints from sets of configuration has received a lot of attentions in the context of reverse engineering of feature models [14]. Many papers [9], [12], [15], [18], [19], [26], [31] in this context propose algorithms to extract constraints from existing configurations. However, all these algorithms only extract constraints without proposing any visualisation mechanisms. Our main objective by introducing FRoGs is not to propose a new extraction algorithm but to contribute a formalism to visualise the mined constraints. Thus, FRoGs can be used as a front-end to visualise constraints using any algorithm.

FRoGs visualisation can be categorized as a radial ego network representation. The ego represents the focal node of the graph. This approach has been used mainly in social network analysis. In software engineering, ego networks has been proposed to visualise how the modification of a given component could demand the evolution of the other components [11] based on the version control system information. FRoGs use ego network representations but it is designed to deal with the specificities of feature relations in SPL.

VI. CONCLUSION & FUTURE WORK

Feature constraints are the core of Feature Models and identifying and maintaining them is challenging in Software Product Line engineering. This paper proposes a new paradigm called FROGs to help domain experts to visualise in an interactive way the feature relations mined from existing configurations. This can help to potentially refine an existing feature model by formalizing new hard and soft constraints. In addition, FROGs can be used to document, at the domain level, each feature by displaying its relations among the rest of features. We demonstrate in this paper the usability of FROGs on a real-world case study from a major manufacturer.

Our future work has two main directions: 1) Regarding to visualisation, FROGs can be improved to consider the time dimension. Indeed, the time dimension in the creation of each existing configuration could help users to understand the dynamicity on feature relations and reason about feature obsolescence or usage over time. 2) Independently from the visualisation aspect, we aim to improve the way that FROGs are built by providing heuristics for default values for the encourage and discourages thresholds.

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