In Three Steps to Software Product Lines: a Practical Example from the Automotive Industry

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ABSTRACT

In the automotive industry, suppliers aim to increase their revenue and try to keep up with the pace of the market trends to stay competitive by offering off-the-shelf products to car manufacturers. On the other hand those car manufacturers request tailored products to gain unique selling points. Each new customer request may result in a new software project. To save time one might find it a good idea to create the new software project as a copy of an older one. This method guarantees initial functionality, but prevents refactoring and leads to continuous software erosion. The implementations diverge from each other and improvements cannot be shared. Software Product Lines (SPL) can help to maximize reusability and quality by building up shared core assets and customer-specific functionality. In our paper, we propose a method to migrate a customer project landscape into a scalable SPL in three steps.

CCS CONCEPTS

• **Software and its engineering** → **Software product lines**; **Reusability**; *Software evolution*; V-model.

KEYWORDS

Software Product Line, migration, adoption, incremental migration, automotive, functionality reuse, active projects

1 INTRODUCTION

Development of product families rather than individual products is a goal for many engineering companies. Product Line Engineering (PLE) is a widely used approach for reaching this goal. It is common and accepted for electronic and mechanical developments and thus especially important for the automotive industry that historically comes from this area [8]. However, for quite some time the automotive industry is constantly moving its focus towards the development of software. This development is still ongoing and becomes more and more complex each year [13]. In order to stay competitive in the future and to realize a competitive advantage, a fast adaption to the market and to customer needs is also required for software. Offering off-the-shelf software products with tailored customer features will increase the company's revenue. Fortunately PLE has also been applied to software engineering for many years already in the form of Software Product Lines (SPL) [9]. An SPL increases reusability [6] and therefore increases quality and decreases development costs of software by building up shared core assets and customer-specific functionality. With this reuse in place, a business will be able to do larger scaling. A higher number of projects will drastically decrease the development costs compared to traditional engineering methods and the time-to-market will improve due to less development effort [5]. Thus an SPL is one possible solution to win against competitors.

But even after years of research, source code migrations to SPL are still complicated and there are no bullet proof concepts available that are applicable to actively running projects with tight release plans. Much research has been done on product line architectures [27, 29] and system engineering [25], about feature model migrations [10–12, 14], SPL evolution [2, 23, 26, 28] and safety aspects [30] of SPLs. On the other hand, Hetrick et al. [15] and Abbas et al. [1] have written about the overall process, general benefits and a change of mindset, but not specifically about source code. Contrary to Rubin et al. [24], cloned variants are no option for us anymore. Krueger [21] reported different migration strategies more than 20 years ago already: (1) proactive, (2) extractive and (3) reactive, but no work described a mixture of extractive and reactive migrations, which we need for existing and upcoming customer

projects. Inspired by the work of Jepsen et al. [18] we aim for a strategy with which we are able to migrate multiple independent repositories to a scalable SPL, allowing developers and software product managers to proceed with their own pace and according to the project plan without risking its deadlines and always being able to do a step backwards if necessary.

In this paper we propose an iterative and incremental migration strategy in three steps. We structured the paper in the following way: Section 2 stating the challenges we faced in our projects and industry to explain our view on the problem and why standard solutions did not work for us, section 3 explaining our three step solution of the source code migration in detail, presenting infrastructure and build system ideas and section 4 presenting our conclusion, an overview on where we stand right now and giving a forecast on future work.

2 CHALLENGE

Our migration method is supposed to be a generic solution, but our company's circumstances might have some influence on the ideas that we share in this paper. This section will explain the challenges we had, both coming from the products' nature and its industry and also from our corporate processes and strategies.

The projects that we migrated are in the area of electric cars for premium automobile manufacturers. The software is written in (Embedded) C and Matlab and modelled with AUTomotive Open System ARchitecture (AUTOSAR) with C code generators. These projects must fulfill Automotive Software Process Improvement and Capability Determination (ASPICE), ISO26262 and other processes, standards and regulations of the automotive industry during their development phases to stay competitive and meet legal requirements. A company will less likely get a new inquiry when the standards and norms are not fulfilled. The standards are relevant for the entire SPL development and do not only apply for the delivered software product, but also for supporting processes and tools like the build system. Additionally, the build system must be able to handle third party source code deliveries without modifications. One example for this are AUTOSAR deliveries. The dependency to a delivered AUTOSAR package is not only a challenge for the toolchain, but also a chance. Due to AUTOSAR's layered architecture and its interface and component design, it already provides modular abstraction for separation of concerns, that can help in building SPL core assets and to maximize functional reuse.

All migrated projects of our SPL base on the same product, a complex sensor cluster. For historic reasons every (customer) project was managed as a separate Dimensions repository. Dimensions is a Source Code Management (SCM) system similar to Revision Control System (RCS) used at the Marquardt GmbH for source code administration and project documentation. Each individual source code repository is a self-contained ready-to-build project, including all required tools and libraries to build the product binaries, like compilers, MSYS and GNU Make. The C code was validated with Jenkins nightly builds. Those Jenkins scripts were located in separate repositories, not part of the project's repository itself. Unit tests were not running with every change of the source code as part of CI/CD, but were running on demand.

Whenever a new customer project was kicked-off, it also triggered the start of a new software project. This software project then started as a clone of another already existing project ('clone-and-own'). This approach had several benefits: the setup time was short and because a mature project was taken as basis, the project's software was stable already and debugging and adapting was possible. There was less work for generic parts and only hardware and customer-specific modifications were required. However, this approach also caused a lot of disadvantages. By simply cloning an existing project there was not only a copy of functionality available in the new project, but also a copy of all its flaws. Because of a large number of copies a possible refactoring of reused code had to be merged back and this meant a high effort. If refactoring is never done, this approach can result in software erosion, as it did in our projects. The software erosion noticeably led to higher maintenance efforts at the end phase of the development and brought up errors late during the product lifecycle. For all the teams working in these projects, with the problems mentioned above, the idea of migrating to another platform including a new tool chain, not only sounded like a mammoth task but unrealistic too, having in mind the tightly planned release schedules.

With our migration to SPL we try to tackle as many as possible of the mentioned challenges. The migration is only partially done and still ongoing, but we did not detect major issues so far. At the same time, we managed to:

- migrate 'clone-and-own' sources to our SPL,
- add variant handling capability to the build system,
- replace the outdated SCM system by Git and Bitbucket,
- introduce a CI/CD system,
- introduce a unit test framework as integral part of the development,
- automate the setup of the build environment and reduce the repository size drastically,
- stay compliant with all rules and norms,
- train the team and
- still keep release plans.

We will not write about all solution aspects in this paper. The focus will be on the source code migration process and less on the tools, processes and performed trainings. Our build system implementation is freely available on Github.com [4].

3 SOLUTION

Our goal with the migration to an SPL is to switch the mindset from 'my project' to 'one of our product variants' by enabling the software teams to collaborate in a single Git repository and be able to use all variants in a single IDE instance to build any target of any product variant. Our SPL implementation uses Visual Studio Code plus CMake Tools extension as IDE, CMake and Ninja for building all required targets, Powershell and Python as build wrapper and CI/CD test runners.

With the help of our SPL implementation we follow a migration strategy that consists of three consecutive steps as depicted in Figure 1.

In an SPL we talk about at least two variation dimensions: space, time [19] and sometimes also maturity [16]. Our first migration step *Complexity Reduction* is merely a step to prepare these dimensions,
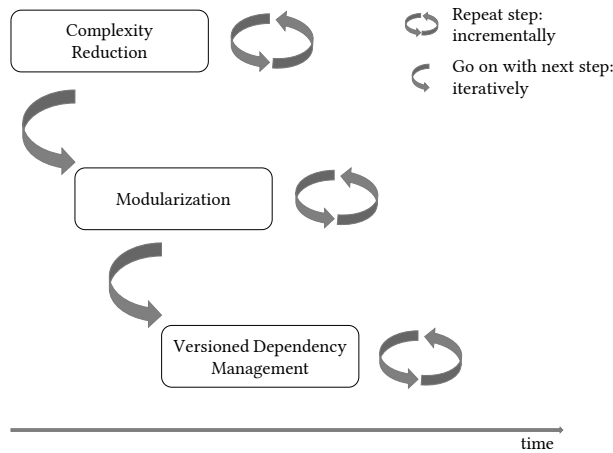
Figure 1: Migration Flow Overview

to bring code together that belongs together within a new SPL-capable build system. The second step *Modularization* enhances the space dimension by building up configurable sources or variants of software components to reduce lines of code and maximize reuse. With variation in space we are able to create feature variants of our software and its components and this is the beginning of the SPL idea. The third step *Versioned Dependency Management* focuses the time dimension and cross-product component reuse.

All three steps will be explained in detail in the following subsections. It is important to know though, that each step can be done incrementally:

- *Complexity Reduction*: variant by variant.
- *Modularization*: component by component.
- *Versioned Dependency Management*: component by component.

If one step is accomplished for a variant or a component, the migration of that specific variant or component can iteratively proceed with the next migration step.

The content of the SPL repository, especially the number of lines of code (LOC), will change during the different migration steps as shown in Figure 2. In the first migration step *Complexity Reduction* the LOC will increase with every legacy project added to the codebase. During *Modularization* legacy sources will be exchanged with configurable sources leading to a reduction of duplicated code and therefore to a decreased LOC. Finally even the LOC of configurable sources in the SPL repository will decrease, as the sources are isolated and moved to a separate repository during the third step *Versioned Dependency Management*. Then those configurable sources will just be configured as external build dependencies in several product families.

3.1 Complexity Reduction

Our first step towards SPL consists of importing several active sensor projects into the SPL, i.e., adding Dimension repository product variants into one structured Git repository. To support further incremental imports of additional sensor variants we implemented a

tool called Transformer [3] that highly automates the necessary import steps. The Transformer is implemented in Python and can be applied to each variant separately, therefore making the transformation incremental and independent of already existing or upcoming variants. The transformation of a legacy project into a new product variant is divided into four parts:

(1) **Copy sources**: The variant's original source tree is copied into a variant-specific legacy tree without any further changes or adaptions.
(2) **Create build configuration**: The original project build system (GNU Make) is used to extract all variant-specific configuration and to transform it into a CMake configuration and part list compatible with the SPL build system.
(3) **Create IDE configuration**: For seamless integration of the SPL repository and its variant concept into Visual Studio Code the CMake Tools extension is used. This extension introduces the concept of CMake Variants, therefore we create a configuration file with build settings for each variant.
(4) **Establish CI/CD**: In order to simplify the switch to the new tool environment, introduce a CI/CD system to increase automation and validation for every source code change.

Switching from variant-specific repositories in Dimensions to a single Git repository in Bitbucket causes a high workflow impact for the developers. Additionally they need to get used to an SPL build system and a new IDE. Therefore, we decided not to change the production source code during this first migration step so that the developers can continue to work in their well-known code basis.

The DevOps Handbook [20] calls this a monolithic approach and positively emphasizes the simplicity and resource efficiency in small scale. It also mentions the drawbacks of overall poor scaling and weak modularization capabilities. We are aware of those drawbacks and are going to tackle them within the third migration step *Versioned Dependency Management*.

The structure after the transformation looks like this:

```
.vscode/
  cmake-kits.json
  cmake-variants.json
  settings.json
legacy/
  variant-a/
    component-1/
    component-2/
  variant-b/
    component-1/
variants/
  variant-a/
    config.cmake
    parts.cmake
  variant-b/
    config.cmake
    parts.cmake
CMakeLists.txt
```

The 'legacy' folder contains all the projects' unmodified source code in variant-specific folders. The configuration and part lists of the variants can be found in the 'variants' folder.
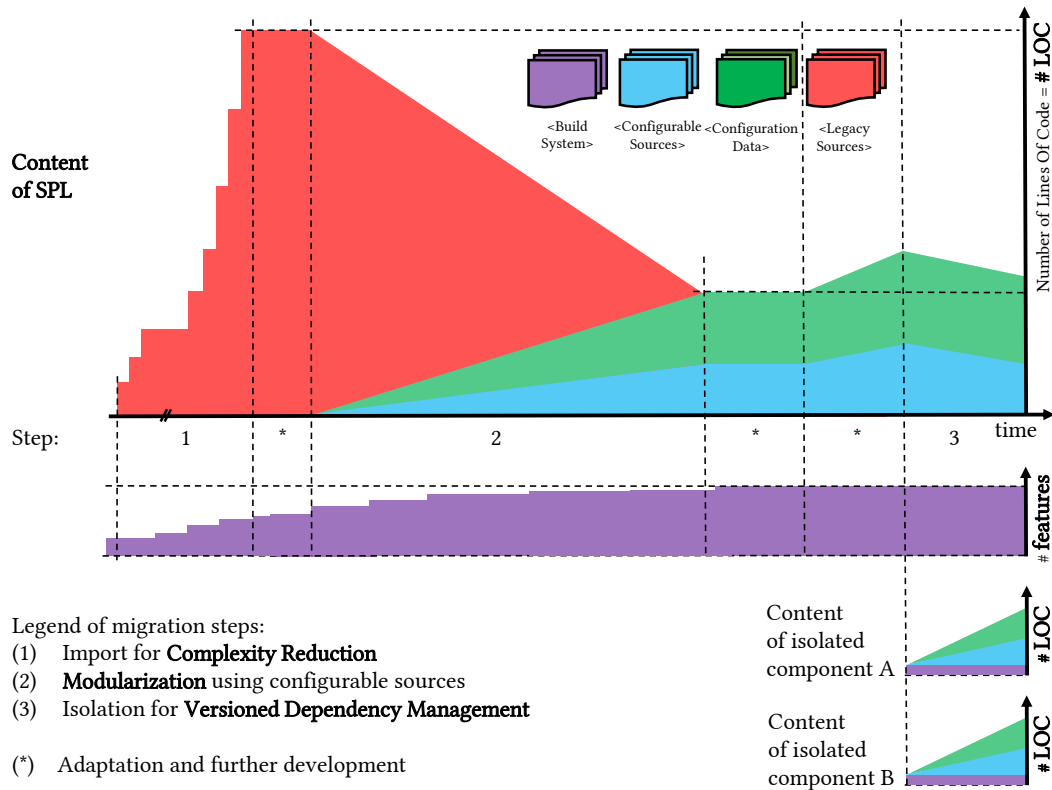
Figure 2: Three Migration Steps to SPL

Although the build system and tool environment is reused already for all variants, for source code there is no reuse in place and the LOC is growing over time as shown in Figure 2, therefore scaling may become problematic. Still there are a lot of advantages with the monolithic way, like centralized deployment with our CI/CD system, start learning to use Git as source code management system and reducing complexity by reducing the number of systems: polyrepo vs. monorepo with a single build system and tool environment.
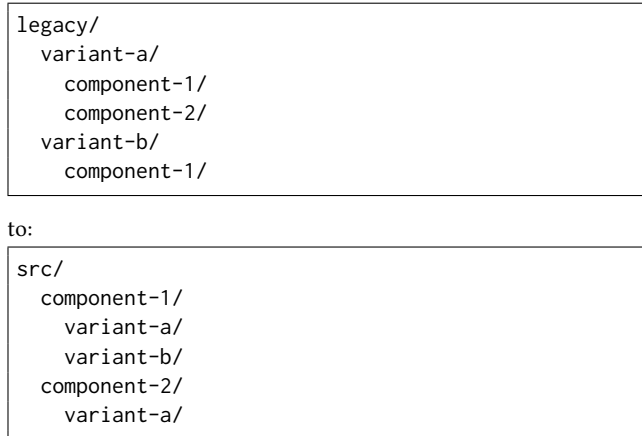
3.2 Modularization

As soon as all developers, software project managers and integrators are used to the outcome of the first step of the SPL migration, the *Modularization* step can begin. With the following three stages it is possible to switch from a project to a product perspective. The goal is to merge the legacy sources into configurable sources, keeping variant-specific functionality, to maximize reuse and reduce maintenance effort. Thinking in terms of products rather than projects helps to reduce the LOC and maximizes the reuse across all variants. In order to build up software components, consisting of core assets and variant-specific functionalities, a feature model is required for configuring the software and thus controlling the execution flow. Although CMake is capable of handling very simple feature models with variables and template generators pretty well, a more complex feature model might require another tool to manage it. Our recommendation for complex feature model configurations

is KConfig, 'a domain specific language designed specifically for coding the Linux kernel variability model' [2, page 3]. KConfig is able to manage the complex design of the Linux kernel and it has enough functionality to work with most embedded applications. Additionally it is open-source and free to use for anyone. Alternative solutions might also fulfill the configuration purpose. Prominent examples are pure:variants [22] from pure systems or Gears from BigLever [17]. Both tools are known to be highly flexible and easy to integrate into existing projects [14].

Independent of the feature model tool the modularization process should be the same. All stages of the *Modularization* step are visible in Figure 3 and will be further described in detail.

Migrate from legacy component to product component: After the first step *Complexity Reduction*, all source code files are located in a dedicated legacy folder. This legacy folder contains a folder for each variant, holding all software components separately. Using a component in multiple variants is possible, but does not make much sense. There is no reason to share the variant component variant-a/component-1 also in variant-b. In this step, components are just moved into a generic source folder. The folder structure will change from:

```
legacy/
  variant-a/
    component-1/
    component-2/
  variant-b/
    component-1/
```

to:

```
src/
  component-1/
    variant-a/
    variant-b/
  component-2/
    variant-a/
```

By doing this, all variants of one component, with the identical or very similar functionality, are moved to the same folder. Variants of a component residing next to each other are easier to compare and to handle. This will enable reuse already, but without the following stages it has no positive effect on LOC reduction or maintenance effort.

Remove duplicates and derive core assets: Within the new structure established in the previous stage, we recommend to clean up duplicate variants. Variants of a component are considered as duplicates if their source code is identical and no configuration is required. This is a fast and easy step for reuse and will not require additional knowledge about a feature model or the functionality. Removing duplicates is followed by separating core assets and variant-specific functionality with a decorator pattern. The separation can be done on a function level and requires static function interface definitions. The concept is to create:

- a core asset C file, which contains generic code across all variants, considered to be static,
- a header file with interface descriptions of core assets and decorators,
- a decorator C file for every variant, which contains a variant-specific implementation of a function; the function signature must be identical for all variants and shall be defined in the according header file.

This way the core assets and the decorators can be developed without any need of conditional compiler directives. It is possible to implement variant-specific differences in an object-oriented manner in C. The idea is to provide a product-specific core asset and additionally one interface with multiple variant-specific decorators that extend the shared functionality. The feature model's responsibility is to take control of the underlying build system and configure the correct decorators. If a separation of core assets and decorators in individual files is not possible or not wanted for any reason, another option would be to use a feature configuration with conditional preprocessor directives or runtime configuration. Toggle points in the code make it possible to select different implementations within the same C file.

Refactor with focus on variability: Last but not least, the code should be refactored according to variability. This is the first stage that has a functional impact on the code, and it requires a mindset change. One must stop thinking about project-specific features and define component-specific features relevant for the product family. Most of the legacy components do not support variability and might require substantial refactoring to have a meaningful feature set.

We highly encourage to implement unit tests before the refactoring starts, if there are no unit tests available already. Refactoring can have effects on the compiled binaries and change the behavior, even though it was not intended by the developer. A feature model will generate many possibilities to configure the software, therefore unit tests covering all core assets and features will ensure that no functionality was broken and will reduce time in finding errors at a later development phase.
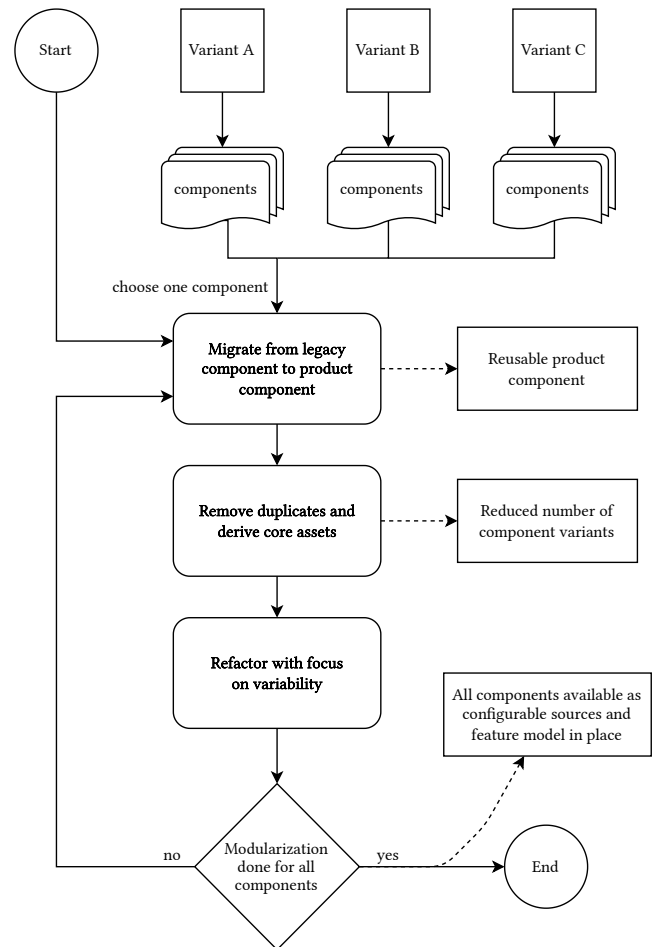

Figure 3: Detailed stages of the *Modularization* step

3.3 Versioned Dependency Management

The first two migration steps focused on the space dimension, how to organize the source code using components and variants. This step deals with the time dimension. By using Git it is already possible to get a variation in time. At any created commit, it is possible to create a new branch. This branch can be the active development branch with all the latest changes, or it can be based on a former

commit to represent a baseline of the SPL that is going to be released or was released already. If bug fixes are required after a release, they will be done on the same release branch. With this strategy, releases can be done on a stable code basis without the influence of new feature developments of other branches. Additionally the documentation of release relevant changes becomes simple. The release branch will stay unchanged and usually not get any feature updates, but only fixes. But release branches in a monorepo come with some drawbacks. It is complicated to get different versions of different components. A baseline must be done on the entire software. An integration of mixed versions is possible but requires lots of manual effort and will likely have a strong negative impact on maintenance. Adding a fix in a component of a specific version in a release branch will not become available in the same version of the same component in any other branch. All commits and branches are independent of each other, so no automatic reuse of code between them is available. Therefore using the same component and version provides no reuse in the space dimension if we introduce the time dimension like this. And finally fixing a bug in a new version, that was spotted in an earlier version, is even more complicated, especially across all branches. Our proposal requires some more changes to the build system and infrastructure. It is required to split up the repository again. With the modularization being done, the split will not be done per project anymore, but per software component. Each modularized software component will reside in its own repository and is maintained separately. This allows us to work with different developers or development teams on different software components independently. To enable the development of a software component in its own repository the following requirements must be fulfilled:

- component specific requirements specifications,
- mocked required interfaces,
- unit tests for all component features in all possible configurations,
- software integration tests and
- a software test plan.

Although this step introduces a polyrepo workflow it still follows the SPL concept by dividing products into smaller pieces still developed in SPL repositories. The SPL repositories of the products do not contain the sources of the isolated components anymore but each SPL repository has dependencies to specific versions (baselines) and variants of the isolated components. These dependencies might be references to commits of a Git repository or to released component package artifacts, e.g., with JFrog Conan.io. This step can be done incrementally again, component by component. The SPL repository's build system will then do the integration job. With a proper dependency management, the build system will integrate requested software components from external repositories of any kind and configure them according to the feature model of the selected variant. The benefits of this approach are the following:

- Components are being developed and tested independently to get a faster release loop.
- A fix of a buggy version is implemented only once in the component's repository.
- Buggy versions can be marked in the components' repositories. With this variant builds containing a buggy version can

print a warning or error. The integrator can then manually update the version of the dependency or justify the warning in regards to their project setup. An automatic update would also be possible.

Since all components are being developed independently, one package version might not be compatible with another component's package. With Conan.io 'compatibility can even be configured and customized on a per-package basis' [7]. This is why we recommend Conan.io over Git submodules or similar techniques. The development team together with their integrators can configure this compatibility check. An AUTOSAR architecture might make this check easier. An application software component should only have interfaces to the Run-Time Environment (RTE), so based on the RTE configuration a compatibility between components should be clearly defined.

Cross-product component reuse: Independent of an SPL introduction, it is most likely that within the product portfolio of an automotive supplier like the Marquardt GmbH with a wide range of different products, those products share similar components and solutions. When such a company applies SPL engineering for one of its products, sooner or later the concept is taken over for other products of other business units, too. In case the second step of SPL migration *Modularization* is finished in at least two SPL repositories with similar core assets and step three has been performed on a few components, the probability, that the need to share those components between the different SPL repositories will arise, is rather high. Therefore the third step of our migration concept provides an additional useful feature: isolation of configurable sources for *Cross-product component reuse*. The idea is that the isolated software component and all its variants can be used in multiple other SPL repositories, not just in one. There are functionalities, e.g., current or voltage measurement, that might be useful in a multitude of electronic products. This can exponentially increase reuse in the entire product portfolio.

4 CONCLUSION AND FUTURE WORK

This work provides an iterative and incremental migration strategy towards SPL for the software of a real-world product family of an automotive supplier. We proposed three steps to perform the migration of a project's software repository to an SPL variant: (1) *Complexity Reduction*, (2) *Modularization* and (3) *Versioned Dependency Management*. It was shown that our proposal can be applied to the repositories of a product family's software at any time of the development phase due to the fact that any of the three steps can be applied incrementally and each transformed variant can iteratively continue with the next migration step independent of the others. With our proposal we:

- established a stable SPL with variants buildable at any time,
- reduced workload of developers by reducing the number of repositories,
- increased collaboration beyond project borders and
- integrated all software sources of a product family into one Git repository.

At the submission date's point of time we managed to proof about 50% of our concept. We implemented a build system with modern CMake fully supporting the concept of SPL variants. The

build system prototype required two persons full-time for six weeks, the implementation for migration step one and two required two persons full-time for three more months. Over a time frame of two months we incrementally added ten variants, while each import to the SPL was really fast due to the automated importing mechanism. We already started with *Modularization* of software components, but only converted a few components and begun with removing duplicates. Recently we focused more on automation than on the SPL migration, as we saw more advantages there in the long run. The automation for CI/CD is helpful for the migration as well.

Nevertheless, the build system requires more features, e.g., a package manager for dependency handling and a unit test framework for Test Driven Development (TDD) to be able to support our migration steps two and three and we plan to implement them in the coming months, in parallel to the *Modularization* of the software components. Additionally it is required to qualify tools which have an impact on the created binaries or the processes to build them. This tool qualification is requested by the ISO 26262 standard for safety reasons. We must take care that CMake, Ninja and KConfig are properly qualified. On the other hand, proprietary software might come with safety evaluations already. This should be kept in mind, when deciding for a future tool landscape.

Besides all the discussed technical challenges, there were also social obstacles on the way to introduce an SPL. Fear of change was probably the strongest emotion we faced. We feared the introduction of our SPL approach, although we were certain that all required build system features were implemented and we always had a backup plan to go back to the original repositories. On the other hand the development team had a lot of doubts to adapt fast enough to new tools and processes. There was no real threat and still no one had enough confidence to start the migration. Afterwards we do not see a reason for hesitation, but sometimes it simply needs someone brave in the team or someone pushing you. Our conclusion is: Just do it! And if you break it, make sure you can fix it fast!

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