

Product line models of large cyber-physical systems: the case of ERTMS/ETCS

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ABSTRACT

A product line perspective may help to understand the possible variants in interactions between the subsystems of a large, cyber-physical system. This observation is exemplified in this paper by proposing a feature model of the family of ERTMS/ETCS train control systems and their foreseen extensions. This model not only shows the different components that have to be installed when deploying the system at the different levels established by the ERTMS/ETCS standards, but it also helps to identify and discuss specific issues, such as the borders between onboard and wayside equipment, different manufacturers of the subsystems, interoperability among systems developed at different levels, backward compatibility of trains equipped with higher level equipment running on lines equipped with lower level equipment, and evolution towards future trends of railway signalling. The feature model forms the basis for formal modelling of the behaviour of the critical components of the system and for evaluating the overall cost, effectiveness and sustainability, for example by adding cost and performance attributes to the feature model.

CCS CONCEPTS

• **Software and its engineering** → **Requirements analysis;**
Software product lines; • **Computer systems organization** →
Embedded and cyber-physical systems;

KEYWORDS

Product lines, variability, feature models, cyber-physical systems, ERTMS/ETCS train control systems

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1 INTRODUCTION

In a globalised economy, enterprises are more and more turning the diversification of products into a marketing strategy to increase their profit. To reduce the development costs and time-to-market of their portfolio of products, systematic reuse of the components constituting these products (systems as well as software) has become common practice.

The aim of (Software or Systems) Product Line Engineering is to introduce such systematic reuse in all phases of product development [21]. Hence, the production, maintenance and management of single products is dealt with in the context of a family or product line of related products, amenable to mass customisation. This engineering approach requires the identification of all core assets of the products in the application domain to be able to successfully exploit their commonality and manage their variability. Variability is defined in terms of features, which can be seen as an (increment in) functionality of a product that is visible or relevant to stakeholders. Feature models, consequently, define those combinations of features that constitute valid products [9, 15].

A product line perspective may help to understand the possible variants in interactions between the subsystems of a large, cyber-physical system, which is characterised by intertwined physical and engineered (software) systems whose operations are monitored, coordinated, and controlled by a computing and communication core [14, 22]. This observation is exemplified in this paper by proposing a feature model of the family of ERTMS/ETCS train control systems and their foreseen extensions. This feature model not only shows the different components that have to be installed when deploying the system at the different levels established by the ERTMS/ETCS standards, but it also helps to identify and discuss specific issues, such as the borders between onboard and wayside equipment, different manufacturers of the subsystems, interoperability among systems developed at different levels, backward compatibility of trains equipped with higher level equipment running on lines equipped with lower level equipment, and evolution towards future trends of railway signalling.

The feature model we propose in this paper can form the basis for formally modelling the behaviour of the critical components of the system and for evaluating the overall cost, effectiveness and sustainability, for example by adding cost and performance attributes to the feature model.

To date, relatively few industrial studies exist concerning the application of product line engineering techniques to the development or management of cyber-physical systems [25].

2 ERTMS/ETCS SYSTEMS PLUS EVOLUTIONS

The increasing need to boost the volume of passenger and freight rail transport and the cost and mere impracticability of constructing new tracks are leading to the aim of running more trains on the existing tracks, raising notable challenges to the operation principles of present railways. The European Railway Traffic Management System (ERTMS)¹ [11] is an international standard that aims to answer these needs by jointly improving the interoperability, performance, reliability, and safety of modern railways.

ERTMS relies on the European Train Control System (ETCS)²: an Automatic Train Protection (ATP) system which continuously supervises the train, ensuring that the safety speed and distance are not exceeded. ERTMS/ETCS is specified in the standard at four main levels of operation, depending on the role of track-side equipment and on the way the information is transmitted to/from trains. We distinguish the following levels (cf. Fig. 1, more details below):

- Level 0 (L0): ETCS-compliant locomotives or rolling stock do not interact with lineside equipment, i.e. because missing ETCS compliance.
- Level NTC (L0-NTC): ETCS-compliant trains are equipped with additional Specific Transmission Modules (STM) for interaction with legacy signalling systems (National Train Control). Inside are standardised ETCS driver interfaces.
- Level 1 (L1): ETCS is installed on lineside (possibly superimposed with legacy systems) and on board; spot transmission of data from track to train occurs via Eurobalises.
- Level 2 (L2): As L1, but Eurobalises are only used for exact train position detection. Continuous data transmission via GSM-R with the Radio Block Centre (RBC) gives the required signalling information to the driver's display. Further lineside equipment is still needed for train integrity detection.
- Level 3 (L3): As L2, but train location and train integrity supervision no longer rely on trackside equipment such as track circuits or axle counters.

We now succinctly describe the main ETCS functionalities that are defined and implemented from Level 1 onwards (cf. Fig. 1), considering also some variations and possible future evolutions.

Level 1 implements an Automatic Train Protection (ATP) functionality, which stops the train in the case the driver does not respect the signals: signals are the sole means in which drivers are authorised to move the train further, according to the national signalling and driving rules. The train's On Board Unit (OBU) knows the distance of the train from the next signal and its aspect by reading special RFID tags named *balises* (or *Eurobalises*), connected to the signals by means of specific Lineside Electronics Units (LEU). The on-board computer continuously monitors and calculates the maximum speed and the braking curve from these data, and the control centre determines the position of the train by means of traditional track-side equipment (such as track circuits) that detects the occupancy of a section of track by a train, determining the location of trains with a coarse granularity.

At Level 2, track-side equipment (track circuits) are maintained to detect the occupancy of a section of track by trains, determining the location of trains with a coarse granularity. This information is

sent to a central unit, the above mentioned RBC, which sends to each train a Movement Authority (MA), computed by summing the free track circuits ahead (*fixed-block signalling*). The MA specifies the maximum distance that a train is allowed to travel, the maximum allowed speed depending on the track morphology (i.e., the static speed profile), and data about the track ahead (e.g., temporary speed restrictions and conditional or unconditional emergency stops). The OBU (a.k.a. European Vital Computer, EVC) of each train uses the MA and data stored on-board (e.g., the braking capability of the train) to compute the braking curve or the dynamic speed profile that determine the speed limit, triggering an emergency brake whenever this limit is exceeded. The train determines its speed via specific sensors (phonic wheel, accelerometer, or radar). The Eurobalises are used as passive positioning beacons or 'electronic milestones' to correct the speed measurement. Level 2 avoids track-side signalling, through a continuous bidirectional communication between the train and the RBC using GSM-R (the railway dedicated GSM), improving line throughput and reducing maintenance costs. ERTMS/ETCS is currently deployed on several lines throughout Europe at most in its Level 2.

Level 3, currently still in development, improves upon the current Level 2 by removing the wayside equipment for detecting the occupancy of track circuits and by giving the on-board odometry system the responsibility to monitor the train position and to compute the current train speed. Specifically, the EVC of each train periodically sends to the RBC the train position. In turn, the RBC sends back to each train an MA, computed by exploiting the knowledge of the position of the rear-end of the foregoing train (*moving-block signalling*), further improving the line throughput and reducing maintenance costs. In doing so, headways between trains can be considerably reduced, in principle to the braking distance.

The concept of Level 3 is defined in [12], but it does not specifically refer to the concept of moving block, admitting any implementation that is able to periodically provide to RBC the position of trains, making little use of trackside equipment. A few pilot implementations, referred as Hybrid L3 [13], use virtual fixed blocks: the line is logically divided in fixed length blocks, and the OBU is in charge of communicating, at specific points of the line (virtual balises), the position of the train, computed on the basis of on-board odometry. The accuracy on position reporting required for the safe distancing between trains suggests that more odometry sensors are used, with proper data fusion algorithms. Moving block based on continuous communication and MA computation is currently implemented in some automatic metros, as a feature of CBTC (Communication Based Train Control) systems.

Main line Level 3 moving block Implementations are still not deployed; one of the main barriers is the need to ascertain train integrity (i.e., that a train has not been physically split into two trains along the line), a problem that has not yet a satisfactory solution for freight trains. Moreover, due to its robust safety requirements, the railway sector is notoriously cautious about adopting technological innovations. Hence, while GNSS-based positioning systems are in use for some time now in the avionics and automotive sectors, current train signalling systems are still based on fixed blocks. However, the faster trains are allowed to run, the longer the braking distance and the longer the blocks need to be, thus decreasing the line's capacity.

¹https://en.wikipedia.org/wiki/European_Rail_Traffic_Management_System

²https://en.wikipedia.org/wiki/European_Train_Control_System

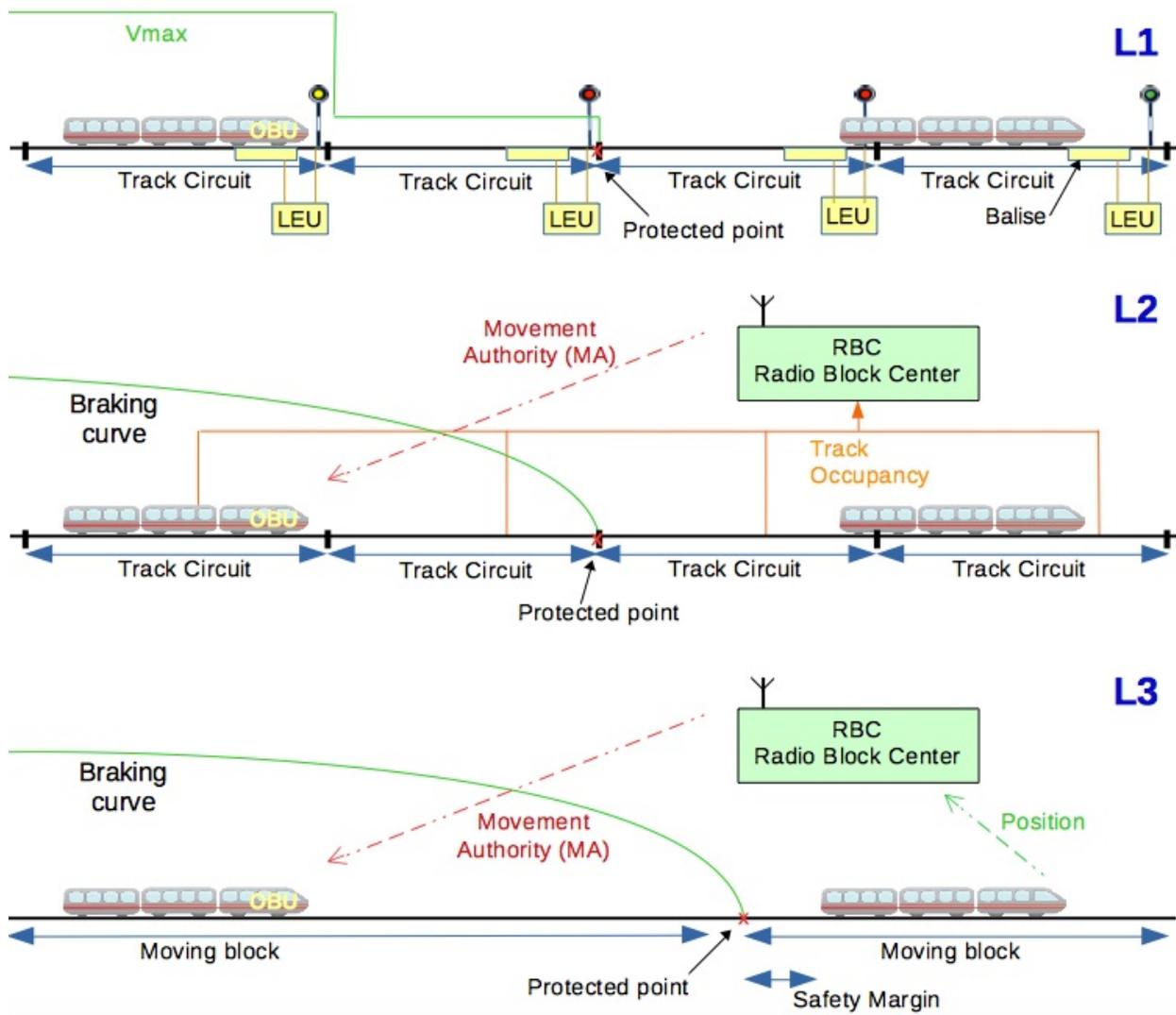


Figure 1: ERTMS/ETCS levels L1, L2, and L3

Therefore, several experiments are being conducted and case studies are being validated [3] in order to base the precise on-board train position computation required by Level 3 on satellite positioning. For this to work, the precise absolute location, speed, and direction of each train is required, which are to be determined by a combination of sensors: active and passive markers along the track, and trainborne speedometers.

One of the current challenges in the railway sector is to make moving block signalling systems as effective and precise as possible, including GNSS and leveraging on an integrated solution for signal outages (think, e.g., of the absence of positioning in tunnels) and the problem of multipaths [23]. This is one of the main topics addressed by the H2020 project in which we are currently involved: ASTRail (SATellite-based Signalling and Automation SysTEms on Railways along with Formal Method and Moving Block Validation) [4, 5] (cf. <http://www.astrail.eu>).

A even more visionary concept is Virtual Coupling (VC), a.k.a. Train Convoys, or ERTMS Level 4 [10, 16, 19], which leverages the availability of safe information about the position, speed, acceleration, and deceleration of the foregoing train to further advance moving-block technology, overcoming the concept of braking curve that keeps in front of a train a long safety zone for a full (emergency) brake to zero speed. Specifically, VC is an innovative method of train formation, based on the idea of multiple trains (possibly individual self-propelling units) running one behind the other, without physical contact but at a distance comparable to mechanical coupling, enabling maximisation of the line capacity. Though far from being implemented in reality, the scenario of Level 3 with VC (L3-VC) is already the subject of an industrial patent [20] and it is one of the challenges considered in the Multiannual Programme of the Shift2Rail Joint Undertaking Initiative [24], which is the innovation programme under which also ASTRail is funded.

3 RELEVANT ISSUES IN ERTMS/ETCS DESIGN

Several issues arise when considering the development of an ERTMS system and its deployment on specific lines.

ERTMS is born from the need of interoperability between national networks, so that trains can cross national borders without the need of lengthy and costly locomotive change. Indeed, many different and incompatible signalling systems are in use in Europe and equipping every locomotive with all the related on-board systems is out of the question. On the other hand, also a simultaneous Europe-wide switch to the new system is not possible, as legacy systems will continue to work side-by-side with ERTMS systems. While newly built, dedicated high-speed corridors are adopting the highest ERTMS/ETCS levels available, European freight corridors, that mostly share traditional lines with local traffic, tend to use lower level ETCS equipment for easier compatibility and lower costs.

In particular, backward compatibility between different levels is an issue: trains equipped with higher level ETCS on-board systems should be able to run on lines controlled by lower level ETCS equipment. Another issue is related to the fact that different manufacturers provide on-board and wayside equipment, and trains equipped by different manufacturers run over lines equipped again by different manufacturers. Moreover, such trains are run by different companies, and lines as well can be maintained by different infrastructure companies (e.g. if they belong to networks of different countries). Proper interfacing is assured by compliance to standards. However, the mentioned emerging new functionalities have not yet been standardised, and the high complexity of the interactions among subsystems does not help a smooth interoperability of heterogeneous equipments. A rigorous description of the overall picture is therefore desirable.

Defining a single well-founded framework encompassing the complexity of the ERTMS/ETCS ecosystem, with its high degree of variability (bound to increase in the future), is a challenge to pursue towards favouring a correct process of planning the development and deployment of such systems by a railway institution, as well as for developing sustainable solutions from involved manufacturers.

4 A FEATURE MODEL FOR ERTMS/ETCS

The research question put forward in this short paper is whether, and how, a product line approach can support such a well-founded framework, due to the ability of variability modelling to capture the structure of a large (cyber-physical) system made up of necessary and optional components and subsystems.

As a first step in this direction, we built a feature model to capture the variability of ERTMS/ETCS systems. It is depicted in Fig. 2. The construction of this model started from the consideration that an ERTMS/ETCS system is made up of three major classes of components, namely the wayside equipment, the on-board equipment, and the radio communication between the two. The corresponding top level features are considered to be abstract, because the concrete systems and components are detailed at the lower level. For the purpose of this paper, the radio communication component is merely concretised in the currently deployed GSM-R system, with the LTE and 5G alternatives foreseen in the next future as reliability and capacity improvements.

The on-board and wayside abstract features have been detailed by means of two different kinds of features:

- Special advanced capabilities added to the basic functionalities (e.g., the moving-block capability (MovBlock) of the wayside equipment and the VC capability (VirtCoup) of rolling stock), considered as optional virtual features, which are in turn implemented through constraints on the existence of supporting concrete features (either as mandatory sub-features or as cross-tree constraints);
- Equipment components, considered as concrete features, that are either mandatory, because present at all ERTMS/ETCS levels, or optional, because used only in some of the levels or some of the variants. Some of these components are further detailed in optional or mandatory sub-features: in particular, odometry, which computes the speed and position of the train, is a critical component at the highest ERTMS/ETCS level and can therefore employ different sensors and algorithms for redundancy, in which case an appropriate data fusion component is also needed; expressing this variability requires the addition of specific cross-tree constraints.

With respect to the aforementioned cross-tree constraints, one more constraint is introduced to mark the necessity of the odometry function for the Location Unit (LU) aimed to compute the positioning of the train.³

This model abstracts from the number of trains and from the number of sections controlled by an RBC, but rather aims to describe the kind of functions, components, and subsystems that are needed at each ERTMS/ETCS level considered. Due to the exploratory nature of the definition of this model, the most commonly encountered issues have been included, while some less important variability has not. In particular, we have considered the RBC and OBU components as mandatory monolithic blocks, due to their necessary presence in charge of computing the MA or braking curves. However, they host different versions of software at the different ERTMS/ETCS levels, and hence they can constitute in their turn a software product family, which is out of the scope of this paper.

5 CONFIGURATION OF ERTMS/ETCS LEVELS

An ERTMS/ETCS system is characterised by its level, as we observed in Section 2. Each level can be considered as a product of the product family presented above; actually, each level still includes some variability, and therefore should be considered as a subfamily.

Table 1 reports typical configurations at different levels: only optional features are shown, apart from the subfeatures of *Satellite*, *data_fusion*, and *RBC2T_Comm* whose selection is left open as an implementation choice (not reported in the table for brevity). Notice that L3 includes several configurations, according to the different degree of innovation that is foreseen for this system: from the bare L3 without moving block, to the adoption of moving block (L3-MB), of satellite positioning (L3-SAT), or even virtual coupling (L3-VC).

The configurations shown in the table satisfy the constraints imposed on the feature model, and indeed are not the only ones satisfying them, also because some different implementation choices can be made in some cases.

³Other acronyms used in Fig. 2: TIMS stands for Train Integrity Monitoring System, TC for Track Circuit, ATO for Automatic Train Operation, and T2T for Train-to-Train.

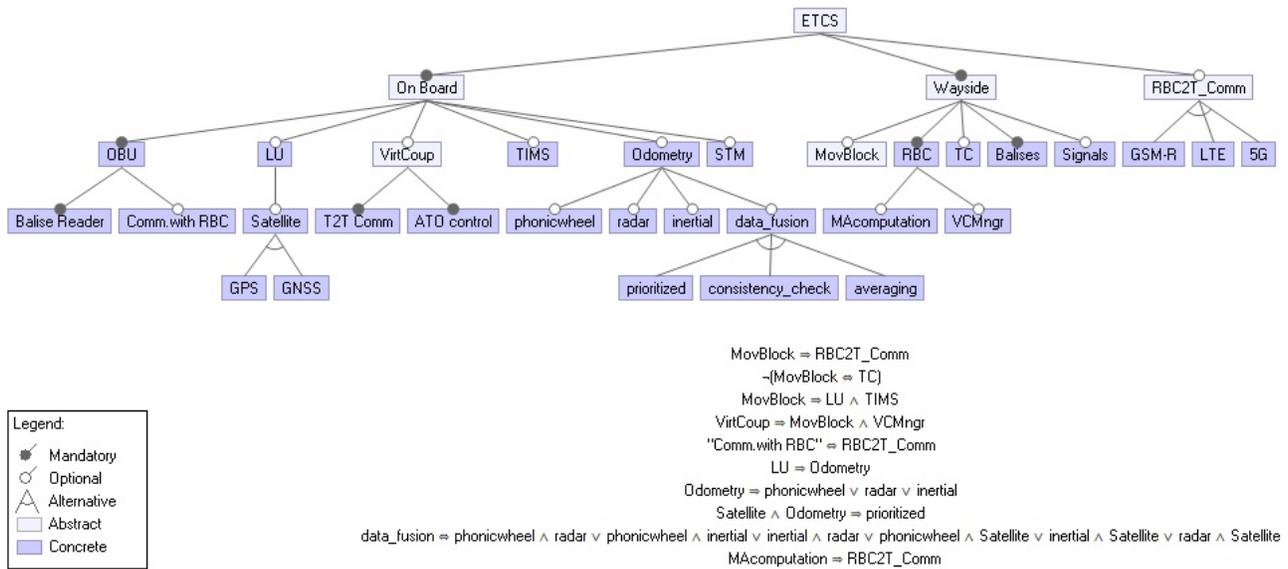


Figure 2: A feature model for ERTMS/ETCS systems (created with FeatureIDE [15])

Table 1: Typical configurations for main ETCS levels

	L0-NTC	L1	L2	L3	L3-MB	L3-SAT	L3-VC
STM	✓						
Comm. with RBC			✓	✓	✓	✓	✓
LU				✓	✓	✓	✓
Satellite						✓	
VirtCoup							✓
TIMS				✓	✓	✓	✓
Odometry			✓	✓	✓	✓	✓
phonicwheel			1	2 or 3	2 or 3	2 or 3	2 or 3
radar			of	of	of	of	of
inertial			3	3	3	3	3
data_fusion				✓	✓	✓	✓
MovBlock					✓	✓	✓
MAcomputation			✓	✓	✓	✓	✓
VCMngr							✓
TC	✓	✓	✓	✓			
Signals	✓	✓					
RBC2T_Comm			✓	✓	✓	✓	✓

Table 2: Evaluating backward compatibility

Train L2 Line L1	Train L3 Line L2	Train L3-VC Line L3	Train L3-VC Line L3-MB
✓	✓	✓	✓
	✓	✓	✓
		✓	✓
	✓	✓	✓
✓	✓	✓	✓
1	2 or 3	2 or 3	2 or 3
of	of	of	of
3	3	3	3
	✓	✓	✓
			✓
✓	✓	✓	✓
✓			
	✓	✓	✓

VirtCoup ⇒ MovBlock ∧ VCMngr

We notice how the definition of cross-cutting constraints turned out to be very useful in the modelling effort in order to understand the existing dependencies among components of an ERTMS/ETCS

system. The support of FeatureIDE in evaluating the constraints over the proposed configurations has been important to reveal some bugs in previous definitions.

6 BACKWARD COMPATIBILITY ISSUES

The configurations listed in Table 2 are related to the coexistence of the same level both in the on-board and in the wayside equipments. On the other hand, a specific requirement for backward compatibility is established in the standard. This means that a train equipped with superior levels of ETCS should be allowed to run on lines equipped with inferior levels, exploiting at best the lower level services offered.

In order to reason on backward compatibility, mixed configurations can be obtained from Table 1 by taking the wayside configuration from one column and the on-board configuration from another (the two parts are separated by double lines in the table).

In Table 2 we show four such cases. The first two columns model an L2 train running on an L1 line and an L3 train on an L2 line, respectively. Both cases result in valid configurations, so there is no apparent conflict. Instead, doing the same for an L3-VC train running on either an L3 line or on an L3-MB line, as depicted in the third and fourth column, respectively, results in an invalid configuration. The grey cells in the two columns represent the conflict, which is due to the constraint $\text{VirtCoup} \Rightarrow \text{MovBlock} \wedge \text{VCMngr}$, which—amongst others—requires that the VC Manager (VCMngr) is present as a function of RBC, a ground-based system, whenever VC (VirtCoup) is selected to be a feature of an on-board system. Actually, this conflict is solved by observing that an L3-VC on-board system running on a lower level line simply is required, through a proper runtime check, not to activate its VC feature VirtCoup. This example shows how the issue of backward compatibility may thus be handled by means of a careful analysis of the feature model and of its intended meaning.

7 CONCLUSION AND FUTURE WORK

In this paper, we have applied a product line perspective to a set of large, cyber-physical systems, namely ERTMS/ETCS train control systems. We have proposed a feature model of the family of ERTMS/ETCS train control systems and their foreseen extensions, and we have shown how this can assist engineers in clarifying the possible configurations that are allowed by the current standards as well as reasoning on backward compatibility among different ERTMS/ETCS levels.

Feature models may also act as facilitators in cost and performance analysis for planning purposes. These attributes can be evaluated and optimised by first decorating the feature models with attributes related to the contribution of each feature to the overall cost (including both investment and maintenance costs) and performance indices, and then applying multi-objective optimisation and quantitative analysis tools.

We have applied this approach in [6–8], where the product line paradigm was applied, at the system engineering level, in order to jointly address variability issues and quantitative analysis of the possible options that a generic bike-sharing system can exhibit. To this aim, feature attributes and global quantitative constraints were added to a feature model, thus creating an attributed feature model suitable to conduct multi-objective optimisation analyses and performance analyses (by means of advanced model-checking techniques), with the purpose of planning the selection of physical

components of the overall system, like the number and kind of bikes and docking stations.

In the above mentioned experiences, we have used FlyFast to assess performance and user satisfaction aspects of variants of large-scale bike-sharing systems by means of mean field model checking in [7]. In [8], we have used QFLan for quantitative analyses ranging from the likelihood of specific behaviour to the expected average cost, in terms of feature attributes, of specific system variants by means of statistical model checking. Finally, for multi-objective optimisation, we have used Clafer, a general-purpose modelling language designed to model features, classes, and meta-models enhanced with complex constraints [2].

Clafer supports the generation of the complete set of instances (products) from such models, possibly with some unresolved variability. Each feature can have one or more associated attributes and quality constraints can be specified either globally or in the context of a feature. This allows one to associate for instance a cost to each feature and a global constraint that only allows products (feature configurations) whose total costs remain within a predefined threshold value. This is a single optimisation objective, but usually there can be more than one attribute associated to a feature, leading to multiple optimisation objectives. In [17], Clafer was used for architectural modelling a realistic automotive scenario.

The ClaferMoo extension was introduced to support attributed feature models and the resulting complex multi-objective optimisation goals [1, 18]. A multi-objective optimisation problem has a set of solutions, known as the Pareto front, representing trade-offs between two or more conflicting objectives. Intuitively, a Pareto-optimal solution is thus such that no objective can be improved without worsening another.

The next step in our modelling effort of a family of ERTMS/ETCS systems is to use these tools to evaluate and compare the different levels from a benefit/cost tradeoff point of view, selecting proper performance indexes and considering both investment and maintenance costs. The information needed to do so will be obtained from discussions with our industrial partners within the ASTRail project, and other ongoing industrial collaborations (cf. <http://stlab.dinfo.unifi.it/sister-project>).

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