Título

Elimination of constraints for parallel analysis of feature models

Autores

José Miguel Horcas, Joaquín Ballesteros, Mónica Pinto, Lidia Fuentes

Conferencia

27th ACM International Systems and Software Product Line Conference (SPLC) - Volume A

Fecha

28 agosto 2023 - 1 septiembre 2023

Palabras clave

Automated analysis, constraint, feature model, feature tree, parallelization, software product line

DOI

https://doi.org/10.1145/3579027.3608981

Resumen

Cross-tree constraints give feature models maximal expressive power since any interdependency between features can be captured through arbitrary propositional logic formulas. However, the existence of these constraints increases the complexity of reasoning about feature models, both for using SAT solvers or compiling the model to a binary decision diagram for efficient analyses. Although some works have tried to refactor constraints to eliminate them, they deal only with simple constraints (i.e., requires and excludes) or require the introduction of an additional set of features, increasing the complexity of the resulting feature model. This paper presents an approach that eliminates all the cross-tree constraints present in regular boolean feature models, including arbitrary constraints, in propositional logic formulas. Our approach for removing constraints consists of splitting the semantics of feature models into orthogonal disjoint feature subtrees, which are then analyzed in parallel to alleviate the exponential blow-up in memory of the resulting feature tree.

References

[Åkesson et al.(2019)] Jonas Åkesson, Sebastian Nilsson, Jacob Krüger, and Thorsten Berger. 2019. Migrating the Android Apo-Games into an annotation-based software product line. In *23rd International Systems and Software Product Line Conference (SPLC)*, Vol. A. ACM, Paris, France, 19:1–19:5. https://doi.org/10.1145/3336294.3342362

[Apel et al.(2013)] Sven Apel, Don S. Batory, Christian Kästner, and Gunter Saake. 2013. *Feature-Oriented Software Product Lines - Concepts and Implementation.* Springer. https://doi.org/10.1007/978-3-642-37521-7

[Audemard and Simon(2018)] Gilles Audemard and Laurent Simon. 2018. On the Glucose SAT Solver. *Int. J. Artif. Intell. Tools* 27, 1 (2018). https://doi.org/10.1142/S0218213018400018

[Batory(2005)] Don S. Batory. 2005. Feature Models, Grammars, and Propositional Formulas. In *9th International Conference on Software Product Lines (SPLC) (LNCS, Vol. 3714)*. Springer, Rennes, France, 7–20. https://doi.org/10.1007/11554844_3

[Benavides et al.(2010)] David Benavides, Sergio Segura, and Antonio Ruiz Cortés. 2010. Automated analysis of feature models 20 years later: A literature review. *Inf. Syst.* 35, 6 (2010), 615–636. https://doi.org/10.1016/j.is.2010.01.001

[Berger et al.(2014)] Thorsten Berger, Rolf-Helge Pfeiffer, Reinhard Tartler, Steffen Dienst, Krzysztof Czarnecki, Andrzej Wasowski, and Steven She. 2014. Variability mechanisms in software ecosystems. *Inf. Softw. Technol.* 56, 11 (2014), 1520–1535. https://doi.org/10.1016/j.infsof.2014.05.005

[Beuche(2019)] Danilo Beuche. 2019. Industrial variant management with pure: : variants. In *23rd International Systems and Software Product Line Conference (SPLC)*, Vol. B. ACM, Paris, France, 64:1–64:3. https://doi.org/10.1145/3307630.3342391

[Camelo et al.(2022)] Miguel Camelo, Marco Gramaglia, Paola Soto, Lidia Fuentes, Joaquín Ballesteros, Antonio Bazco Nogueras, Gines Garcia-Aviles, Steven Latré, Andres Garcia-Saavedra, and Marco Fiore. 2022. DAEMON: A Network Intelligence Plane for 6G Networks. In *IEEE Globecom 2022 Workshops*. IEEE, 1341–1346. https://doi.org/10.1109/GCWkshps56602.2022.10008662

[Czarnecki et al.(2005)] Krzysztof Czarnecki, Simon Helsen, and Ulrich W. Eisenecker. 2005. Formalizing cardinality-based feature models and their specialization. *Softw. Process. Improv. Pract.* 10, 1 (2005), 7–29. https://doi.org/10.1002/spip.213

[Czarnecki and Wasowski(2007)] Krzysztof Czarnecki and Andrzej Wasowski. 2007. Feature Diagrams and Logics: There and Back Again. In *11th International Software Product Lines Conference (SPLC)*. IEEE, Kyoto, Japan, 23–34. https://doi.org/10.1109/SPLINE.2007.24

[Darwiche and Marquis(2002)] Adnan Darwiche and Pierre Marquis. 2002. A knowledge compilation map. *Journal of Artificial Intelligence Research* 17 (2002), 229–264.

[Fernández-Amorós et al.(2014)] David Fernández-Amorós, Ruben Heradio, José Antonio Cerrada, and Carlos Cerrada. 2014. A Scalable Approach to Exact Model and Commonality Counting for Extended Feature Models. *IEEE Trans. Software Eng.* 40, 9 (2014), 895–910. https://doi.org/10.1109/TSE.2014.2331073

[Galindo et al.(2016)] José Angel Galindo, Mathieu Acher, Juan Manuel Tirado, Cristian Vidal, Benoit Baudry, and David Benavides. 2016. Exploiting the enumeration of all feature model configurations: a new perspective with distributed computing. In *20th International Systems and Software Product Line Conference (SPLC)*. ACM, Beijing, China, 74–78. https://doi.org/10.1145/2934466.2934478

[Galindo and Benavides(2020)] José A. Galindo and David Benavides. 2020. A Python framework for the automated analysis of feature models: A first step to integrate community efforts. In *24th ACM International Systems and Software Product Line Conference (SPLC)*, Vol. B. Montreal, Canada, 52–55. https://doi.org/10.1145/3382026.3425773

[Ghamizi et al.(2019)] Salah Ghamizi, Maxime Cordy, Mike Papadakis, and Yves Le Traon. 2019. Automated search for configurations of convolutional neural network architectures. In *23rd International Systems and Software Product Line Conference (SPLC)*, Vol. A. ACM, Paris, France, 21:1–21:12. https://doi.org/10.1145/3336294.3336306

[Gil et al.(2010)] Yossi Gil, Shiri Kremer-Davidson, and Itay Maman. 2010. Sans Constraints? Feature Diagrams vs. Feature Models. In *14th International Software Product Lines Conference (SPLC): Going Beyond*, Vol. 6287. Springer, Jeju Island, South Korea, 271–285. https://doi.org/10.1007/978-3-642-15579-6_19

[Gramaglia et al.(2022)] Marco Gramaglia, Miguel Camelo, Lidia Fuentes, Joaquín Ballesteros, Gabriele Baldoni, Luca Cominardi, Andres Garcia-Saavedra, and Marco Fiore. 2022. Network Intelligence for Virtualized RAN Orchestration: The DAEMON Approach. In *Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*. 482–487. https://doi.org/10.1109/EuCNC/6GSummit54941.2022.9815816

[Guo et al.(2014)] Jianmei Guo, Edward Zulkoski, Rafael Olaechea, Derek Rayside, Krzysztof Czarnecki, Sven Apel, and Joanne M. Atlee. 2014. Scaling

exact multi-objective combinatorial optimization by parallelization. In *29th IEEE/ACM International Conference on Automated Software Engineering (ASE)*. ACM, Vasteras, Sweden, 409–420. https://doi.org/10.1145/2642937.2642971

[Halin et al.(2019)] Axel Halin, Alexandre Nuttinck, Mathieu Acher, Xavier Devroey, Gilles Perrouin, and Benoit Baudry. 2019. Test them all, is it worth it? Assessing configuration sampling on the JHipster Web development stack. *Empir. Softw. Eng.* 24, 2 (2019), 674–717. https://doi.org/10.1007/s10664-018-9635-4

[Hentze et al.(2022)] Marc Hentze, Chico Sundermann, Thomas Thüm, and Ina Schaefer. 2022. Quantifying the variability mismatch between problem and solution space. In *25th International Conference on Model Driven Engineering Languages and Systems (MODELS)*. ACM, Montreal, Canada, 322–333. https://doi.org/10.1145/3550355.3552411

[Heradio et al.(2022)] Ruben Heradio, David Fernández-Amorós, José A. Galindo, David Benavides, and Don S. Batory. 2022. Uniform and scalable sampling of highly configurable systems. *Emp. Soft. Eng.* 27, 2 (2022). https://doi.org/10.1007/s10664-021-10102-5

[Heradio et al.(2019)] Ruben Heradio, David Fernández-Amorós, Christoph Mayr-Dorn, and Alexander Egyed. 2019. Supporting the statistical analysis of variability models. In *41st International Conference on Software Engineering (ICSE)*. IEEE / ACM, Montreal, Canada, 843–853. https://doi.org/10.1109/ICSE.2019.00091

[Heradio et al.(2016)] Ruben Heradio, Hector Perez-Morago, David Fernández-Amorós, Roberto Bean, Francisco Javier Cabrerizo, Carlos Cerrada, and Enrique Herrera-Viedma. 2016. Binary Decision Diagram Algorithms to Perform Hard Analysis Operations on Variability Models. In *15th New Trends in Software Methodologies, Tools and Techniques (SoMeT) (Frontiers in Artificial Intelligence and Applications, Vol. 286)*. Larnaca, Cyprus, 139–154. https://doi.org/10.3233/978-1-61499-674-3-139

[Heß et al.(2021)] Tobias Heß, Chico Sundermann, and Thomas Thüm. 2021. On the scalability of building binary decision diagrams for current feature models. In *25th ACM International Systems and Software Product Line Conference (SPLC)*, Vol. A. ACM, Leicester, United Kingdom, 131–135. https://doi.org/10.1145/3461001.3474452

[Horcas(2018)] José Miguel Horcas. 2018. *WeaFQAs: A Software Product Line Approach for Customizing and Weaving Efficient Functional Quality Attributes*. phdthesis. Universidad de Málaga. https://hdl.handle.net/10630/17231

[Horcas et al.(2022a)] José Miguel Horcas, José A. Galindo, and David Benavides. 2022a. Variability in data visualization: a software product

line approach. In *26th ACM International Systems and Software Product Line Conference (SPLC)*, Vol. A. ACM, Graz, Austria, 55–66. https://doi.org/10.1145/3546932.3546993

[Horcas et al.(2023a)] José Miguel Horcas, José A. Galindo, Ruben Heradio, David Fernández-Amorós, and David Benavides. 2023a. A Monte Carlo tree search conceptual framework for feature model analyses. *J. Syst. Softw.* 195 (Jan. 2023), 111551. https://doi.org/10.1016/j.jss.2022.111551

[Horcas et al.(2022b)] José Miguel Horcas, José Angel Galindo, Mónica Pinto, Lidia Fuentes, and David Benavides. 2022b. *FM fact label*: a configurable and interactive visualization of feature model characterizations. In *26th ACM International Systems and Software Product Line Conference (SPLC)*, Vol. B. ACM, Graz, Austria, 42–45. https://doi.org/10.1145/3503229.3547025

[Horcas et al.(2023b)] José Miguel Horcas, Mónica Pinto, and Lidia Fuentes. 2023b. Empirical analysis of the tool support for software product lines. *Softw. Syst. Model.* 22, 1 (2023), 377–414. https://doi.org/10.1007/s10270-022-01011-2

[Horcas et al.(2023c)] José Miguel Horcas, Mónica Pinto, and Lidia Fuentes. 2023c. A modular metamodel and refactoring rules to achieve software product line interoperability. *J. Syst. Softw.* 197 (2023), 111579. https://doi.org/10.1016/j.jss.2022.111579

[Horcas et al.(2022c)] Jose Miguel Horcas, Daniel Struber, Alexandru Burdusel, Jabier Martinez, and Steffen Zschaler. 2022c. We're Not Gonna Break It! Consistency-Preserving Operators for Efficient Product Line Configuration. *IEEE Transactions on Software Engineering* (2022), 1–1. https://doi.org/10.1109/TSE.2022.3171404

[Ignatiev et al.(2018)] Alexey Ignatiev, António Morgado, and João Marques-Silva. 2018. PySAT: A Python Toolkit for Prototyping with SAT Oracles. In *21st International Conference on Theory and Applications of Satisfiability Testing (SAT) (LNCS, Vol. 10929)*. Springer, Oxford, UK, 428–437. https://doi.org/10.1007/978-3-319-94144-8_26

[Kang et al.(1990)] Kyo C Kang, Sholom G Cohen, James A Hess, William E Novak, and A Spencer Peterson. 1990. *Feature-oriented domain analysis (FODA) feasibility study*. Technical Report. Carnegie-Mellon University. CMU/SEI-90-TR-21.

[Knüppel et al.(2017)] Alexander Knüppel, Thomas Thüm, Stephan Mennicke, Jens Meinicke, and Ina Schaefer. 2017. Is there a mismatch between real-world feature models and product-line research?. In *11th Joint Meeting on Foundations of Software Engineering (ESEC/FSE)*. ACM, 291–302. https://doi.org/10.1145/3106237.3106252

[Knüppel(2016)] Alexander Knüppel. 2016. *The Role of Complex Constraints in Feature Modeling.* Master's Thesis. Technische Universität Braunschweig. https://www.isf.cs.tu-bs.de/cms/team/knueppel/downloads/thesisKnueppel16.pdf

[Kowal et al.(2016)] Matthias Kowal, Sofia Ananieva, and Thomas Thüm. 2016. Explaining anomalies in feature models. In *15th ACM SIGPLAN International Conference on Generative Programming (GPCE): Concepts and Experiences.* ACM, Amsterdam, The Netherlands, 132–143. https://doi.org/10.1145/2993236.2993248

[Krieter(2020)] Sebastian Krieter. 2020. Large-scale T-wise interaction sampling using YASA. In *24th ACM International Systems and Software Product Line Conference (SPLC)*, Vol. A. Montreal, Canada, 29:1–29:4. https://doi.org/10.1145/3382025.3414989

[Liang et al.(2015)] Jia Hui Liang, Vijay Ganesh, Krzysztof Czarnecki, and Venkatesh Raman. 2015. SAT-Based Analysis of Large Real-World Feature Models is Easy. In *19th International Conference on Software Product Line (SPLC).* ACM, New York, NY, USA, 91–100. https://doi.org/10.1145/2791060.2791070

[Lopez-Herrejon and Batory(2001)] Roberto E. Lopez-Herrejon and Don S. Batory. 2001. A Standard Problem for Evaluating Product-Line Methodologies. In *3rd International Conference on Generative and Component-Based Software Engineering (GCSE) (LNCS, Vol. 2186).* Springer, Erfurt, Germany, 10–24. https://doi.org/10.1007/3-540-44800-4_2

[Lopez-Herrejon et al.(2014)] Roberto Erick Lopez-Herrejon, Javier Ferrer, Francisco Chicano, Evelyn Nicole Haslinger, Alexander Egyed, and Enrique Alba. 2014. A parallel evolutionary algorithm for prioritized pairwise testing of software product lines. In *16th Genetic and Evolutionary Computation Conference (GECCO).* ACM, Vancouver, BC, Canada, 1255–1262. https://doi.org/10.1145/2576768.2598305

[Martinez et al.(2018)] Jabier Martinez, Xhevahire Tërnava, and Tewfik Ziadi. 2018. Software product line extraction from variability-rich systems: the robocode case study. In *22nd International Systems and Software Product Line Conference (SPLC)*, Vol. 1. ACM, Gothenburg, Sweden, 132–142. https://doi.org/10.1145/3233027.3233038

[Mendonça(2009)] Marcílio Mendonça. 2009. *Efficient Reasoning Techniques for Large Scale Feature Models.* Ph. D. Dissertation. University of Waterloo. https://hdl.handle.net/10012/4201

[Mendonça et al.(2009)] Marcílio Mendonça, Andrzej Wasowski, and Krzysztof Czarnecki. 2009. SAT-based analysis of feature models is easy. In *13th International Software Product Lines Conference (SPLC)*, Vol. 446. ACM, San

Francisco, California, USA, 231–240. https://dl.acm.org/citation.cfm?id=1753267

[Mendonça et al.(2008)] Marcílio Mendonça, Andrzej Wasowski, Krzysztof Czarnecki, and Donald D. Cowan. 2008. Efficient compilation techniques for large scale feature models. In *7th International Conference on Generative Programming and Component Engineering (GPCE)*. ACM, 13–22. https://doi.org/10.1145/1449913.1449918

[Müller et al.(2000)] Martin Müller, Joachim Niehren, and Andreas Podelski. 2000. Ordering Constraints over Feature Trees. *Constraints An Int. J.* 5, 1/2 (2000), 7–41. https://doi.org/10.1023/A:1009866317252

[Oh et al.(2019)] Jeho Oh, Paul Gazzillo, and Don S. Batory. 2019. t-wise coverage by uniform sampling. In *23rd International Systems and Software Product Line Conference (SPLC)*, Vol. A. ACM, 15:1–15:4. https://doi.org/10.1145/3336294.3342359

[Pett et al.(2021)] Tobias Pett, Sebastian Krieter, Tobias Runge, Thomas Thüm, Malte Lochau, and Ina Schaefer. 2021. Stability of Product-Line Samplingin Continuous Integration. In *15th International Working Conference on Variability Modelling of Software-Intensive Systems (VaMoS)*. 18:1–18:9. https://doi.org/10.1145/3442391.3442410

[Schmitt et al.(2018)] Anna Schmitt, Georg Rock, and Christian Bettinger. 2018. Glencoe – A Tool for Specification, Visualization and Formal Analysis of Product Lines. In *25th International Conference on Transdisciplinary Engineering*, Vol. 7. Modena, Italy, 665–673. https://doi.org/10.3233/978-1-61499-898-3-66

[Schobbens et al.(2007)] Pierre-Yves Schobbens, Patrick Heymans, Jean-Christophe Trigaux, and Yves Bontemps. 2007. Generic semantics of feature diagrams. *Comput. Networks* 51, 2 (2007), 456–479. https://doi.org/10.1016/j.comnet.2006.08.008

[She et al.(2010)] Steven She, Rafael Lotufo, Thorsten Berger, Andrzej Wasowski, and Krzysztof Czarnecki. 2010. The Variability Model of The Linux Kernel. In *4th International Workshop on Variability Modelling of Software-Intensive Systems (VaMoS) (ICB-Research Report, Vol. 37)*. Universität Duisburg-Essen, Linz, Austria, 45–51. http://www.vamos-workshop.net/proceedings/VaMoS_2010_Proceedings.pdf

[Shi et al.(2019)] Kai Shi, Huiqun Yu, Jianmei Guo, Guisheng Fan, Liqiong Chen, and Xingguang Yang. 2019. A Parallel Framework of Combining Satisfiability Modulo Theory with Indicator-Based Evolutionary Algorithm for Configuring Large and Real Software Product Lines. *Int. J. Softw. Eng. Knowl. Eng.* 29, 4 (2019), 489–513. https://doi.org/10.1142/S0218194019500219

[Shi et al.(2018)] Kai Shi, Huiqun Yu, Jianmei Guo, Guisheng Fan, and Xingguang Yang. 2018. A parallel portfolio approach to configuration optimization for large software product lines. *Softw. Pract. Exp.* 48, 9 (2018). https://doi.org/10.1002/spe.2594

[Siegmund et al.(2012)] Norbert Siegmund, Marko Rosenmüller, Martin Kuhlemann, Christian Kästner, Sven Apel, and Gunter Saake. 2012. SPL Conqueror: Toward optimization of non-functional properties in software product lines. *Softw. Qual. J.* 20, 3-4 (2012), 487–517. https://doi.org/10.1007/s11219-011-9152-9

[Sundermann et al.(2021a)] Chico Sundermann, Kevin Feichtinger, Dominik Engelhardt, Rick Rabiser, and Thomas Thüm. 2021a. Yet another textual variability language?: a community effort towards a unified language. In *25th ACM International Systems and Software Product Line Conference (SPLC)*, Vol. A. https://doi.org/10.1145/3461001.3471145

[Sundermann et al.(2022)] Chico Sundermann, Kevin Feichtinger, José A. Galindo, David Benavides, Rick Rabiser, Sebastian Krieter, and Thomas Thüm. 2022. Tutorial on the universal variability language. In *26th ACM International Systems and Software Product Line Conference (SPLC)*, Vol. A. 260. https://doi.org/10.1145/3546932.3547024

[Sundermann et al.(2023)] Chico Sundermann, Tobias Heß, Michael Nieke, Paul Maximilian Bittner, Jeffrey M. Young, Thomas Thüm, and Ina Schaefer. 2023. Evaluating state-of-the-art # SAT solvers on industrial configuration spaces. *Empir. Softw. Eng.* 28, 2 (2023), 29. https://doi.org/10.1007/s10664-022-10265-9

[Sundermann et al.(2021b)] Chico Sundermann, Michael Nieke, Paul Maximilian Bittner, Tobias Heß, Thomas Thüm, and Ina Schaefer. 2021b. Applications of #SAT Solvers on Feature Models. In *15th International Working Conference on Variability Modelling of Software-Intensive Systems (VaMoS)*. 12:1–12:10. https://doi.org/10.1145/3442391.3442404

[Thüm(2020)] Thomas Thüm. 2020. A BDD for Linux?: the knowledge compilation challenge for variability. In *24th ACM International Systems and Software Product Line Conference (SPLC)*, Vol. A. 16:1–16:6. https://doi.org/10.1145/3382025.3414943

[Thüm et al.(2014a)] Thomas Thüm, Sven Apel, Christian Kästner, Ina Schaefer, and Gunter Saake. 2014a. A Classification and Survey of Analysis Strategies for Software Product Lines. *ACM Comput. Surv.* 47, 1 (2014), 6:1–6:45. https://doi.org/10.1145/2580950

[Thüm et al.(2014b)] Thomas Thüm, Christian Kästner, Fabian Benduhn, Jens Meinicke, Gunter Saake, and Thomas Leich. 2014b. FeatureIDE: An extensible framework for feature-oriented software development. *Sci. Comput.*

Program. 79 (2014), 70–85. https://doi.org/10.1016/j.scico.2012.06.002

[Tieber and Felfernig(2021)] Robert Tieber and Alexander Felfernig. 2021. A Knowledge-based Configurator for Building Magic: The Gathering Card Decks. In *23rd International Configuration Workshop (ConfWS)*, Vol. 2945. CEUR-WS.org, Vienna, Austria, 55–57. https://ceur-ws.org/Vol-2945/42-RT-ConfWS21_paper_3.pdf

[Turner(1985)] D. A. Turner. 1985. Miranda: A Non-Strict Functional language with Polymorphic Types. In *Functional Programming Languages and Computer Architecture (FPCA) (LNCS, Vol. 201)*. Springer, 1–16. https://doi.org/10.1007/3-540-15975-4_26

[van den Broek and Galvão(2009)] Pim van den Broek and Ismênia Galvão. 2009. Analysis of Feature Models using Generalised Feature Trees. In *3rd International Workshop on Variability Modelling of Software-Intensive Systems (VaMoS)*, Vol. 29. 29–35. http://www.vamos-workshop.net/proceedings/VaMoS_2009_Proceedings.pdf

[van den Broek et al.(2008)] Pim van den Broek, Ismênia Galvão, and Joost Noppen. 2008. Elimination of Constraints from Feature Trees. In *Workshop on Analyses of Software Product Lines (ASPL) @ SPLC'08*, Vol. Second (Workshops). Limerick, Ireland, 227–232.

[Vidal et al.(2021)] Cristian Vidal, Alexander Felfernig, José A. Galindo, Müslüm Atas, and David Benavides. 2021. Explanations for over-constrained problems using QuickXPlain with speculative executions. *J. Intell. Inf. Syst.* 57, 3 (2021), 491–508. https://doi.org/10.1007/s10844-021-00675-4

[Young(2005)] Trevor J. Young. 2005. *Using AspectJ to build a software product line for mobile devices.* Ph. D. Dissertation. University of British Columbia. https://doi.org/10.14288/1.0051632