Using mCRL2 for the Analysis of Software Product Lines

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Outline

QUANTICOL: A Quantitative Approach to Management and Design of Collective and Adaptive Behaviours

EU FP7-ICT FET-Proactive STREP: 1 April 2013 – 31 March 2017

- University of Edinburgh, Scotland, Jane Hillston (Coordinator)
- CNR-ISTI, Pisa, Italy, Mieke Massink
- University of Southampton, England, Mirco Tribastone
- EPFL, Lausanne, Switzerland, Jean-Yves Le Boudec
- IMT Lucca, Italy, Rocco De Nicola

Collective Adaptive Systems (CAS)

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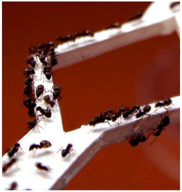
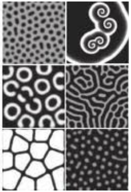
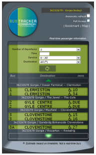
Many examples of decentralized collective adaptive behavior in nature



QUANTICOL: focus on applications arising in context of smart cities





Highly distributed systems with adaptive behavior relying on continuous feedback of vast numbers of consumers and producers

Characteristics of CAS and the project

- Coordination based on (local) decentralized interaction
- Large scale, heterogeneous agents, competing goals, open
- Capacity to smoothly adapt to changing circumstances
- Spatially inhomogeneous distribution influences global patterns
- Multiple scales in time and space, systems of systems
- Decentralized and centralized control

Vision: develop an innovative formal design framework consisting of

- mathematical (quantified) representations of the dynamic behavior of spatially inhomogeneous CAS
- a formal specification language and quantified logic for CAS
- tool-supported, scalable analysis and verification techniques
- design patterns for emergent behavior and control over spatially distributed CAS

QUANTICOL @ CNR-ISTI-FMT

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- Scalable verification approaches (model checkers)
- Quantitative business models and product families

Concrete case study on bike-sharing systems (BSS)

- Popular sustainable means of transportation in urban environment
- Challenging case study offering interesting runtime optimization problems and exhibiting variability in the kind of features and in their quantitative characteristics

T3.3 Relating local and global system views with variability analysis

- Study relations between (representations of) small populations and compact (family) representation of large population 'built' from them by indicating the commonalities and variabilities of single entities in their overall environment

(Software) Product Line Engineering

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To develop a family of products (product line) using a shared platform or architecture (commonalities) and mass customization (variabilities)

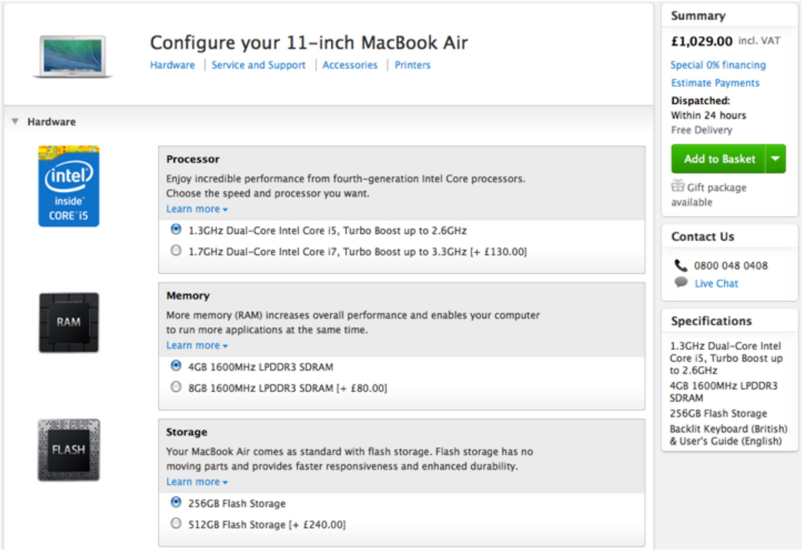
Aim: maximize commonalities whilst minimizing cost of variations (i.e., of individual products), thus specifically facilitating (software) reuse in a predictive manner

Variability in terms of features:

- End-user visible pieces of functionality that represent both commonalities (e.g., mandatory, required) and variabilities (e.g., optional, alternative)
- Only specific combinations of features concern valid products

Complex: *"We always have 126,000,000 different bicycles in store! But only the parts for 1,000..."*

Example (1/2)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4GB 1600MHz LPDDR3 SDRAM
256GB Flash Storage
Backlit Keyboard (British) & User's Guide (English)

Example (2/2)

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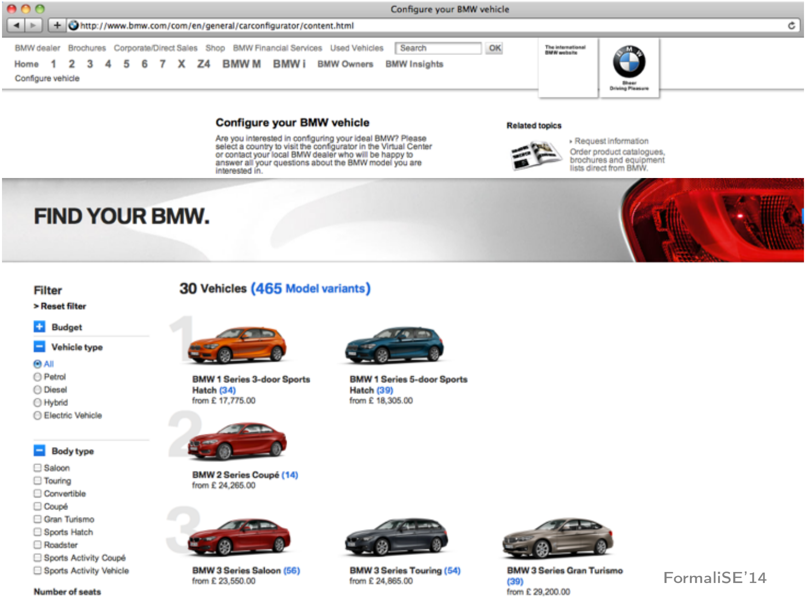

Attributed feature model: A compact representation of all the family's products

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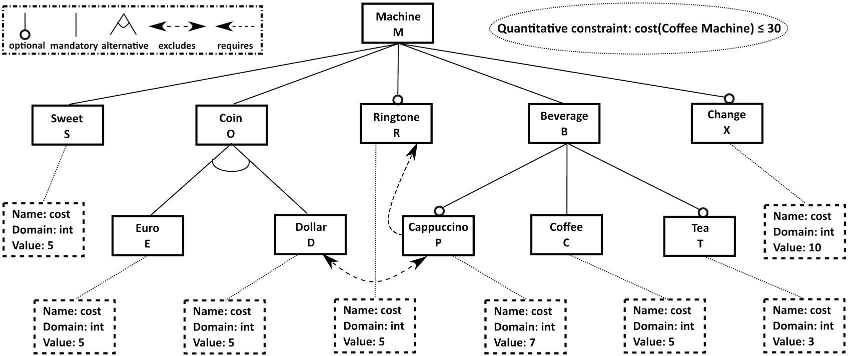
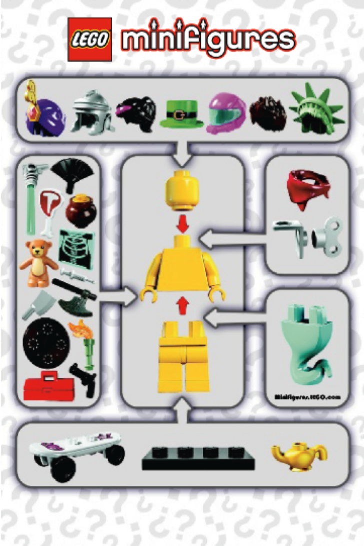


Non-functional attributes: $cost\,(product) = \sum\{\ cost\,(feature) \mid feature \in product\ \}$

From $2^{10} - 1 \xrightarrow{\text{feature diagram}} 2^5 \xrightarrow{\text{cross-tree constraints}} 20 \xrightarrow{\text{attributes}} 16$ valid products !

Family of 16 valid products
(i.e., feature combinations)

'feature model'
(allowing >16)



Formal methods in SPLE

Computer-aided analysis of variability models

- Traditionally: focus on modeling/analyzing structural constraints
- But: software systems often embedded/distributed/safety-critical
- Important: model/analyze also behavior (e.g., quality assurance)

Goal: rigorously establish critical requirements of (software) systems
⇒ lift success stories from single product/system engineering to SPLE

Recent approaches to formally model behavioral variability:

- Variants of UML diagrams (Haugen et al., Jézéquel et al.)
- Extensions of Petri nets (Clarke et al.)
- Models with LTS-like semantics: MTS (Fischbein et al., Fantechi et al.), I/O automata (Larsen et al., Lauenroth et al.), CCS/CSP (Gruler et al., Gnesi et al., ter Beek et al.), FTS (Classen et al.), FSM (Millo et al.)

Scalability is a major issue!
(slide by C. Kästner, CMU)

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Using mCRL2 for behavioral analysis

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"adopt and extend state-of-the-art analysis tools"

"examine[s] only valid product variants"

"visualize and (manually or automatically) analyze feature combinations corresponding to products of the product line"

"support (feature) modularity"

Recommendations for Improving the Usability of Formal Methods for Product Lines
(J.M. Atlee, S. Beidu, N.A. Day, F. Faghih & P. Shaker @ FormaliSE'13)

Modularization (in a feature-oriented fashion) are made concrete in ter Beek & de Vink @ ISoLA'14

(Fisler & Krishnamurthi @ ESEC/FSE'01 first recognized that most properties of interest naturally decompose around features)

mCRL2: www.mcrl2.org (open source)

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Formal, process-algebraic specification language for distributed and concurrent systems + associated industrial-strength toolset ($>$60)

Built on μCRL (1990), mCRL2 since 2003, now actively maintained

Up to 10^5 states per second, state spaces of size 10^9 are the norm

Symbolic exploration of 10^6 states per second, state spaces of 10^{12}

Built-in datatypes (Bool, Int, Real, Sets, Functions) + user-defined abstract datatypes to parametrize actions

Formal methods used incl. linear processes, (parametrized) Boolean equation systems, LTS, modal μ-calculus with data (incl. LTL, CTL)

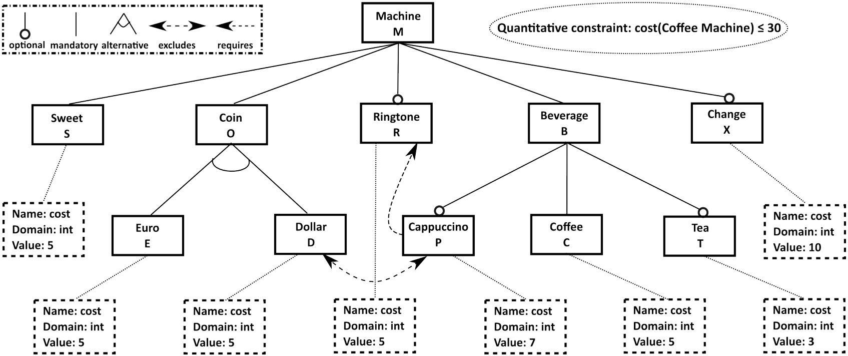
Simulation, visualization, behavioral reduction, model checking, etc.

Highly optimized, up-to-date (i.e. best-known algorithms implemented)

A family of coffee machines

- Initially, money must be inserted: either at least one euro's worth in coins, *exclusively* for European products, or at least one dollar's worth in coins, *exclusively* for Canadian products
- Input of money can be canceled via a cancel button. *Optionally*, the machine returns change after more than one euro or one dollar was inserted
- Once the machine contains at least one euro or one dollar, the user has to choose whether (s)he wants sugar, by pressing one of two buttons, after which (s)he can select a beverage
- The choice of beverage (coffee, tea, cappuccino) varies, but coffee *must* be offered by *all* products whereas cappuccino *may* be offered *solely* by European products
- *Optionally*, a ringtone *may* be rung after delivering a beverage. A ringtone *must* however be rung by *all* products offering cappuccino
- After the beverage is taken, the machine returns idle

Recall: attributed feature model



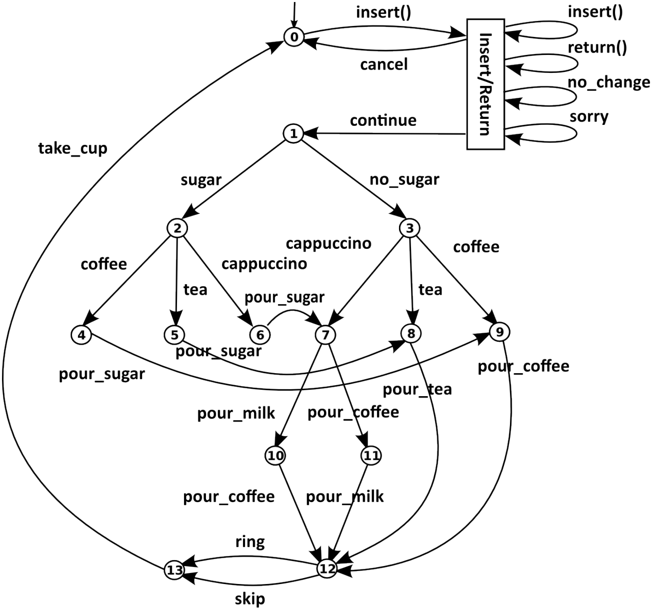
Selection process: specification induced by feature diagram, CTCs, cost


```
proc Sel(st:Int,fs:FSet) =
...
(st == 1) -> ( (M in fs) -> ( set0 . Sel(2,insert(O,fs) ) ) )
+
(st == 2) -> ( (M in fs) -> ( tau . Sel(3,fs) +
                              setR . Sel(3,insert(R,fs)) ) )
+
...

(st == 8) -> ( ( (D in fs) && (P in fs) ) -> wrong_set . delta <>
               ( !(R in fs) && (P in fs) ) -> wrong_set . delta <>
               ctc_ok . Sel(9,fs) )
+

(st == 9) -> ( (tcost(fs) <= 30) ->
               set_ok(fs) . cost(tcost(fs)) . Prod(0,fs) <>
               wrong_set . delta )
;
```

LTS modeling family behavior



Product + Insert processes: specification of valid behavior induced by LTS


```
proc Prod(st:Int,fs:FSet) =
(st == 0) -> ( Insert(0,fs) ) +
...
(st == 2) -> ( (C in fs) -> coffee . Prod(4,fs) +
               (T in fs) -> tea . Prod(5,fs) +
               (P in fs) -> cappuccino . Prod(6,fs) ) +
...

proc Insert(bal:Nat,fs:FSet) =
(bal < 100) -> (
  (D in fs ) -> ( ... ) +
  (E in fs) -> ( insert(ct10) . Insert(bal+10,fs) +
                 insert(ct20) . Insert(bal+20,fs) +
                 insert(ct50) . Insert(bal+50,fs) +
                 insert(euro) . Insert(bal+100,fs) ) ) +
((bal > 0) && (bal < 100)) -> Return(bal,fs) . cancel . Prod(0,fs) +
(bal >= 100) ->
  ( ( ( !(X in fs) ) -> no_change . continue . Prod(1,fs) <>
  Return(Int2Nat(bal-100),fs) . continue . Prod(1,fs) ) )
;
```

Product behavior abstracting from . . .

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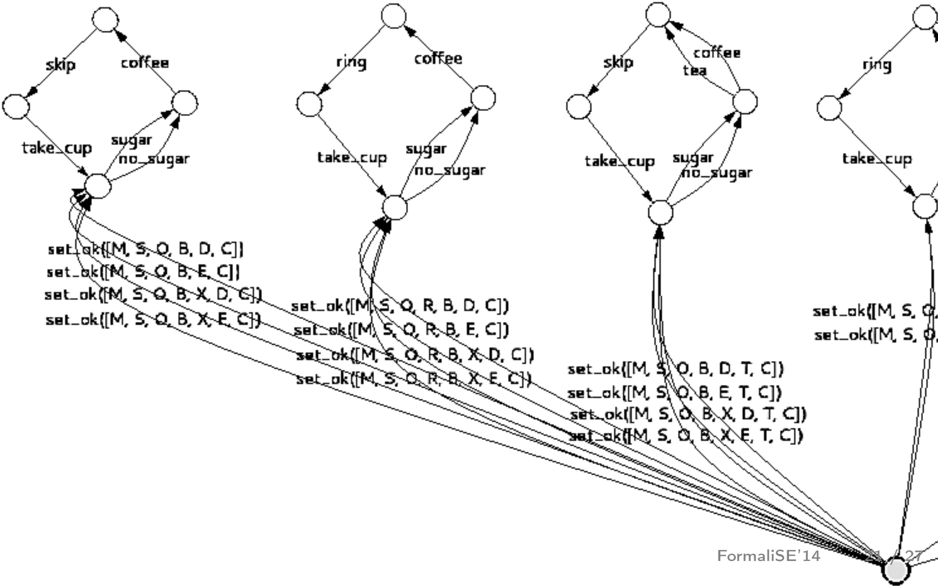
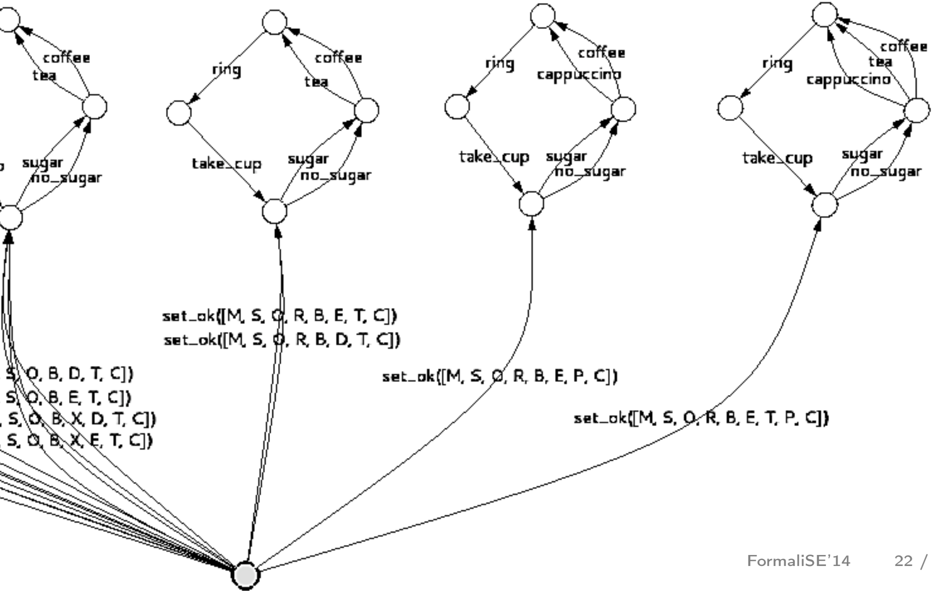


. . . configuration and payment

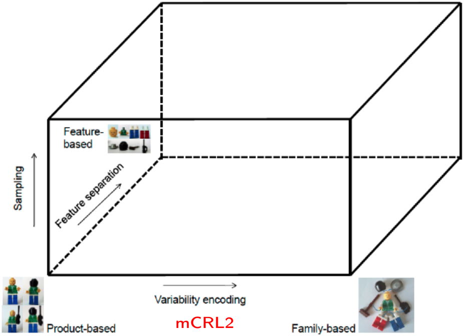


Model checking properties in modal μ-calculus with data using mCRL2

- If payment is not settled by action `continue`, no beverage is delivered:
  ```
  [(!continue)*.take_cup] false
  ```
- Once the X-feature is selected, action `no_change` will not occur:
  ```
  [true*.setX.true*.no_change] false
  ```
- If a product is configured successfully as indicated by the `set_ok` action, then it cannot be a product that accepts dollars and provides cappuccino:
  ```
  forall fs:FSet.val(isSet(fs)) && [true*. set_ok(fs)]true =>
  val((D in fs) => !(P in fs))
  ```
- From the initial state, after a finite number of steps, either action `set_ok` (with some parameter `fs`) or action `wrong_set` occurs:
  ```
  mu Y.(<exists fs:FSet.set_ok(fs)>true || <wrong_set>true ||
  [true]Y)
  ```
- After money has been inserted, in a finite number of steps, a beverage can be taken unless the transaction was canceled:
  ```
  forall c:Coin.[true*.insert(c)]
  mu Y.(<cancel || take_cup> true || [true]Y )
  ```

Position in the PLA cube (Apel et al.)

Sampling based on coverage criteria such as pairwise or *t*-wise coverage (or other heuristics)



Possible trade-off?

- Brute-force product-based analysis with model checkers highly optimized for single system engineering (e.g., SPIN, mCRL2)
- Highly innovative family-based analysis with model checkers developed specifically for SPL (e.g., SNIP by Classen et al.)

⇒ An evaluation of mCRL2 might lead to the desire to implement some SPL-specific features into its model-checking algorithms

Publicity (1/3): Open Call for Papers

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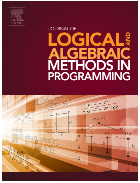
Special Issue on
Formal Methods in Software Product Line Engineering



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Guest editors:

- Maurice ter Beek (ISTI-CNR, Pisa, Italy)
- Dave Clarke (U Uppsala, Sweden & KU Leuven, Belgium)
- Ina Schaefer (TU Braunschweig, Germany)

Publicity (2/3): SPLC'14 in Florence

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Publicity (3/3): deadlines in June!

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