Automated Conflict Detection Between Medical Care Pathways

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What is the Problem?

In England $>$ 15 million people have a long-term health condition.

Around 70% of the money spent on health and social care.

In the UK 2.9 million with three or more (Multi-morbidity) – by 2018.

- aging, smoking, diet, inactivity, ...
- cancer, heart disease, lung disease, diabetes, depression, ...

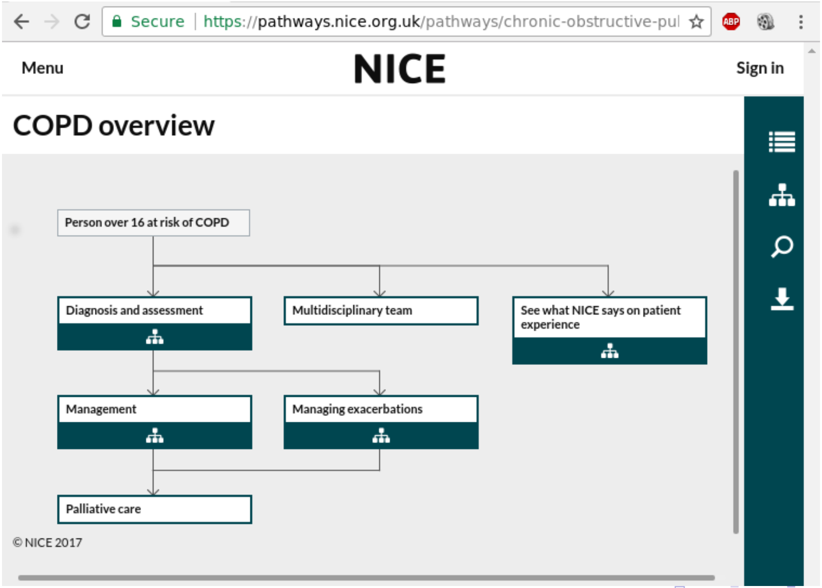
Complex processes for treatment (people, factors, clinical evidence ...)

UK National Institute for Care Excellence (NICE):

- Clinical Guidelines $\rightarrow$ Care Pathways.

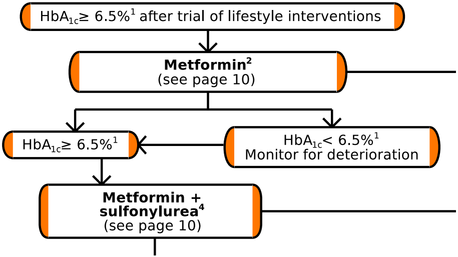
A care pathway is essentially a process for treatment of a disease.

Care Guidelines and Pathways



Two Problems

1. Informal modelling – potential for inconsistency,
2. Focus on single conditions – potential for conflict.



- Implicit cycle of retesting.
- What does Metformin conflict with?
- What does HbA1c interact with?

Our work:

1. define a formal pathway model to capture clinical pathways,
2. develop automated methods for conflict detection,
3. recommend minimal solutions for conflict resolution.

1. Modelling clinical guidelines

Modelling Clinical Guidelines

Requirement: formal modelling for analysis.
Many options (YAWL, Petri Nets, Computer Interpretable Guidelines, ...)

Business Process Model and Notation (BPMN):

- well-known *de facto* business process modelling language,
- increasingly prevalent for modelling clinical pathways,
- graphical, intuitive, flexible, 'subset-able'.

But

- no formal semantics,
- models can be unstructured,
- especially the semantics w.r.t. data are unspecified.

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Data in Care Pathways

Routing may be dependent on and modify data, e.g.

- Is patient already taking medication m?
- If test $X >$ value v, refer for treatment X else retest in M months.
- If patient age $A > a$ prescribe drug x else y.
- Record the fact of prescription of drug Z.

BPMN has the Data Object element, but

- semantics open to interpretation,
- decoupled from the control-flow.

Literature covering formalisation of

- BPMN integration with data objects, e.g. [Meyer et al., 2013];
- interaction between processes and databases [Sun et al., 2014];
- seems more complex than we need;
- similarly the data semantics of YAWL or Computer Interpretable Guidelines.

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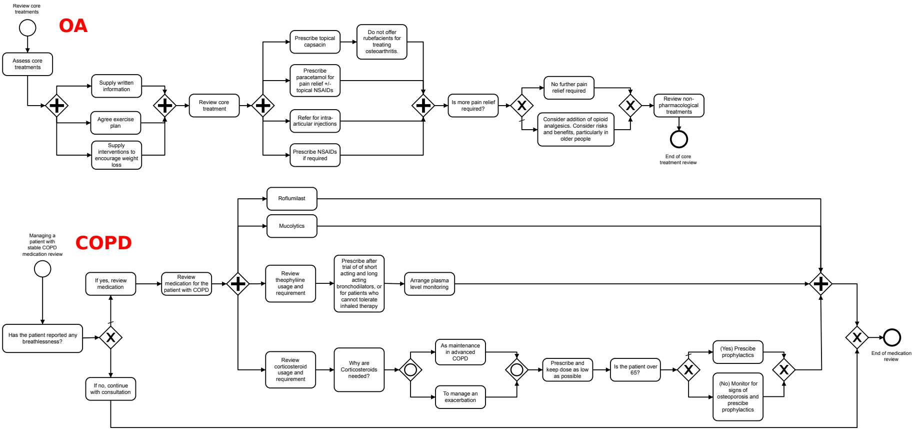
BPMN for Two Pathway Fragments



Fragments of doctors' appointments for review of

OA : Osteoarthritis.

COPD : Chronic Obstructive Pulmonary Disease (Lung Disease).

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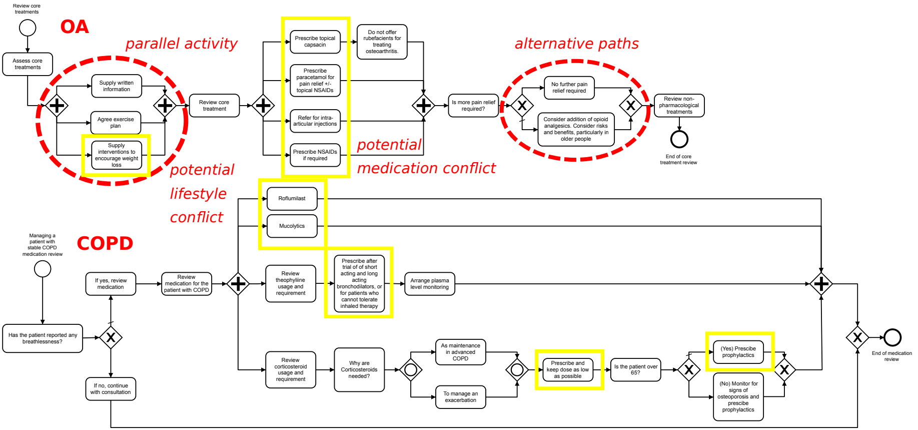

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BPMN+V: Data-Enhanced BPMN

Formal execution semantics . . .

- subset of BPMN notation – can be expanded,
- formal semantics of execution,
- based on Workflow Graphs ([Vanhatalo et al., 2007] formalism),

. . . and integration with data,

- semantics of dependence on – and modification of – data,
- based on Coloured Petri Nets.

Workflow Graphs

Effectively a subset of BPMN allowing the main control-flow patterns and imposing some structure on the model [Vanhatalo et al., 2007].

- $G = (N, E)$, nodes N, edges E, such that $E \subseteq N \times N$,
- $N \in \{\textsc{Start}, \textsc{Stop}, \textsc{Activity}, \textsc{Fork}, \textsc{Join}, \textsc{Decision}, \textsc{Merge}\}$,
- G is well-formed by definition,
- allowing for atomic activities, parallel and alternative behaviours.

Semantics of G is a *token game* (*cf* Petri Nets).

- *State* s of G is a mapping $s : E \rightarrow \mathbb{N}$ assigning *tokens* to edges in E.
- $s(e) = k \iff$ in state s, edge e carries $k \in \mathbb{N}$ tokens.
- execution of node n changes the state to $s' : s \xrightarrow{n} s'$.

This says nothing about data.

BPMN+V: Modelling Data

Flexible approach to model data:

- Fixed set of d variables $X = \{x_1, \ldots, x_d\}$ of types $\mathcal{T}(x_i) \in \{\mathcal{T}_1, \ldots, \mathcal{T}_m\}$,
- valuations $V = (\nu_1, \ldots, \nu_d)$ assigned to X as the process executes.
  - V assigned to token ('colour').
- Activity may be guarded by pre- and post-*conditions* $c(\cdot)$:
  - $c(\cdot)$ is a first-order logic formula over X,
  - $c(\cdot) \vDash V$ if the valuation V satisfies $c(\cdot)$,
  - e.g. $pre(a) := c(x_1, \ldots, x_d) \triangleq (x_i > 55)$.
- Activity may carry out *data modifications*:
  - statement $f(\cdot) : V \rightarrow V'$ over variables in X,
  - e.g. $x := x + 1$ or $x := False$,
- data may require synchronisation – managing the control-flow.

Implicit data is referenced but not modified.

– e.g. database of drug-drug-disease interactions (Stockley / BNF).

BPMN+V: Execution Semantics

Extension of Workflow Graphs:

- $G = (N, l, E, X, pre, post, mod)$,
- $l : N \to \{\textsc{Start}, \textsc{End}, \textsc{Activity}, \textsc{Exclusive}, \textsc{Inclusive}, \textsc{Parallel}\}$,
- $X = \{X_1, \ldots, X_d\}$,
- $\{pre, post\} : N \to C$,
- $mod : N \to D$ (database),
- allowing for atomic activities, parallel, exclusive or inclusive choice.

Semantics defined in terms of before- and after- conditions and states,

- $m : E \to \{T_1, T_2, \ldots\}$ is a *marking* decribing the *state*,
- mapping each edge $e \in E$ to coloured tokens, $T_i = (t_i, V_i)$,
- execution modifies the *state* $m \xrightarrow{n} m'$ and (perhaps) *valuation* $V \to V'$.

BPMN+V: Execution Semantics

e.g. For an ACTIVITY a in a well-formed BPMN+V model:

- one input and one output sequence flow e_{in}, e_{out}.
- a consumes $T = (t, V)$ from e_{in} and returns $T' = (t, V')$ on e_{out},
- if $\exists T = (t, V) \in m(e_{in}) \mid pre(a) \vDash V$, // V satisfies any pre-condition.
- then $m \xrightarrow{a} m'$, where

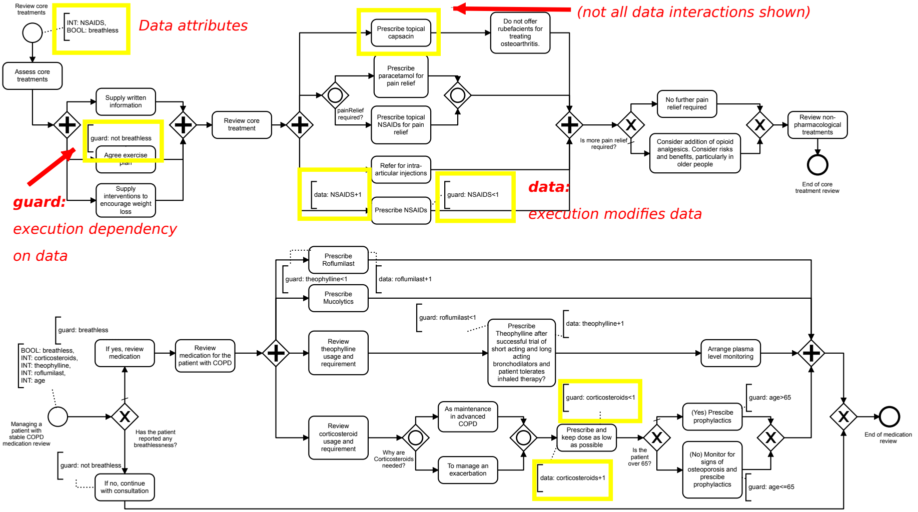
1. $post(a) \vDash V'$, and
2. $m'(e) =$

$$\begin{cases} m(e) \setminus \{T\} & \text{if } e = e_{in}, \quad // V' \textit{ satisfies any post} - \textit{condition.} \\ m(e) \cup \{T'\} & \text{if } e = e_{out}, \quad // \textit{ token is 'moved'}. \\ m(e) & \text{otherwise.} \end{cases}$$

e.g. $pre(a) := \neg$NSAIDS,
$f(a) \triangleq$ corticosteroids := corticosteroids + 1.

– Similarly for all node types.

BPMN+V: Data Annotation



2. Conflict Detection

Conflict Detection

The problem: to identify conflicts between clinical care guidelines followed concurrently in treating patients with multiple morbidities.

Assume

- two BPMN+V models (care pathways) M_1, M_2,
- interacting with database $\mathcal{D}$,
- shared set of d variables $X = X_1 \cup X_2$,
- set of k *constraints* $C = \{C_1, \ldots, C_k\}$.

Constraint C_r is a logical formula over X, e.g.

- if x_i and x_j indicate prescription of two medications,
- which must not be taken together,
- then $C_r(x_1, \ldots, x_d) \triangleq \neg(x_i \wedge x_j)$.

The problem:

identify all pairs of execution paths through M_1, M_2 which will modify the variables in X so that at least one of the C is violated.

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State Space Approach to Conflict Detection

Current process for conflict detection (evaluate BPMN+V):

1. Model clinical pathways in BPMN+V,
2. simple parallel composition,

Assumes patient (potentially) starts both pathways concurrently.
Assumes no common activities.

Future: intelligent model composition.

State Space Approach to Conflict Detection

Current process for conflict detection (evaluate BPMN+V):

1. Model clinical pathways in BPMN+V,
2. simple parallel composition,
3. annotate with constraints (potential conflicts, e.g. meds. dependencies),
4. identify data combinations for which to explore the model,

– Identify d variables X involved in conditions,
– values V checked/assigned.

– Create a 'covering set' of 2^d initial data settings for validation:

  – e.g. $\{y > 1, y \leq 1\}$ for a condition $y > 1$.

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4. identify data combinations for which to explore the model,
5. state space exploration for each data combination (via CPN),

– Transform to CPN (take advantage of existing methods).
– Construct 2^d reachability graphs R_i (explore state space).

– Conflicting Activities indicated by non-final dead markings
linked by common variables.

– Repeat for individual models (detect data-related inconsistencies)
– and composed models (detect conflicts).

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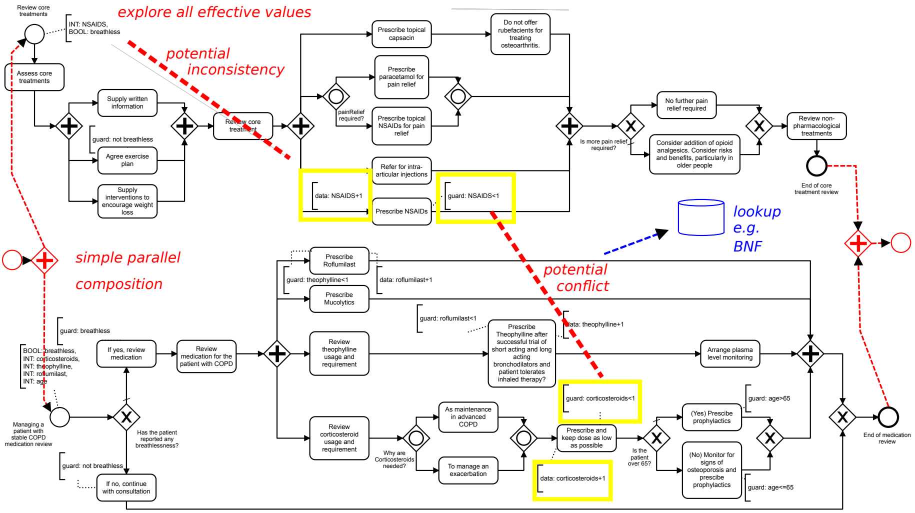
4. identify data combinations for which to explore the model,
5. state space exploration for each data combination (via CPN),
6. identify 'non-final dead markings',
7. visualise and interpret the conflicting activities and data combinations.

Composed OA and COPD Model



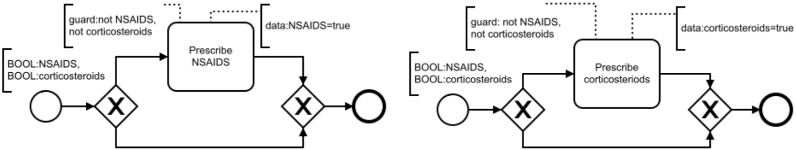
(Possibly invalid assumption that the patient starts following both models at the same time.)

3. Evaluation

Evaluation

3-stage evaluation:

1. Artificial process fragments, e.g.



2. Randomly-generated models,
   - block-structured expansion,
   - controlled block probabilities and number of conflicts.

3. Running example – Osteoarthritis (OA) and COPD pathways,
   - 14 activities,
   - 3 variables,
   - up to $11,000$ states in the composed model.

Report and Visualise Results

Model	Activity	Data	Initial Data	Conflict Model	Conflict Activity	Conflict Data
OA	Agree exercise plan [¬breathless]	breathless=True	breathless=True			
OA	Prescribe NSAIDs	NSAIDS=1	NSAIDS=1			
COPD	Prescribe cortico. and keep …	cortico.=1	cortico.=1			
COPD	Prescribe roflumilast [th.lline< 1]	th.lline=1	th.lline=0	COPD	Prescribe th.lline after …	rofl.
COPD	Prescribe th.lline … [rofl.< 1]	rofl.=1	rofl.=0	COPD	Prescribe roflumilast	th.lline
OA	Prescribe NSAIDs	cortico.=1	cortico.=0	COPD	Prescribe and keep …	NSAIDS
COPD	Prescribe cortico. and keep …	NSAIDS=1	NSAIDS=0	OA	Prescribe NSAIDs	cortico.

data inconsistencies for OA (top),

- cannot proceed with exercise plan if patient presents with breathlessness,
- must not over-prescribe NSAIDS.

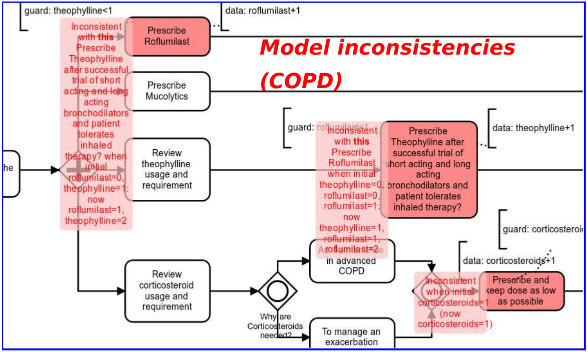
COPD (centre),

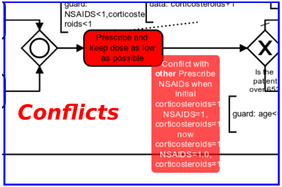
- must not over-prescribe corticosteroids,
- check/prescribe Roflumilast and Theophylline are mutually exclusive,
- but parallel structure allows both to be executed.

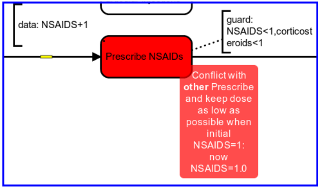
conflicts between the models (bottom).

- corticosteroids and NSAIDs are mutually exclusive across both pathways.

Report and Visualise Results







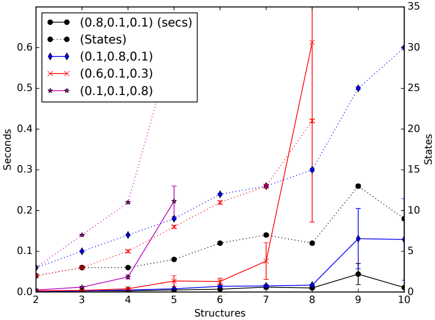
"Inconsistent with **this** {activity} when {data settings}".

"Conflict with **other** {activity} when {data settings}".

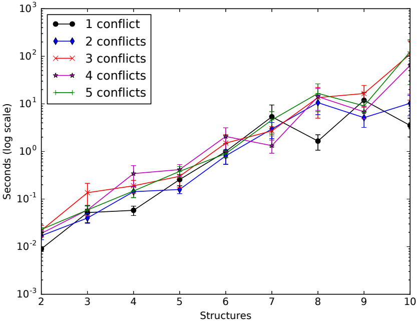
Annotation using `http://bpmn.io/` and/or Camunda Modeller.

Conflict Detection: Performance of State Space Method

Bespoke BPMN+V and CPN implementation.
Averages over 30 randomly generated models.



(a) Varying complexity models [$p(seq)$, $p(xor)$, $p(pll)$].

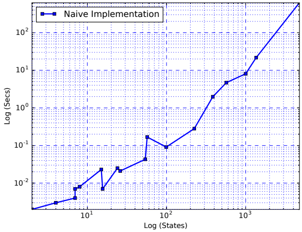


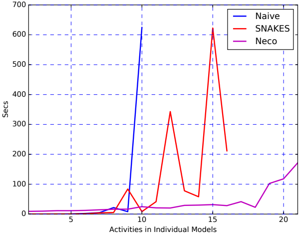
(b) Composed models, varying numbers of conflicts.

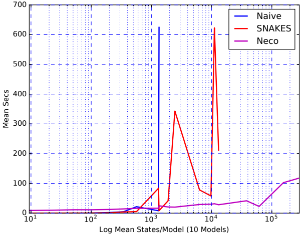
(a) #states *vs* time (seconds) to run the conflict detection process,
– models generated with varying probability of sequence, alternate or parallelism.
(b) increasing #conflicts, in models with low probability of concurrent activity.

Conflict Detection: Performance of State Space Method

Bespoke *vs* SNAKES [1] *vs* Neco [2].
Averages over 30 randomly generated models.







[1] SNAKES: `https://snakes.ibisc.univ-evry.fr/`

"SNAKES is a Python library that provides all the necessary to define and execute many sorts of Petri nets",

[2] Neco: `https://github.com/Lvyn/neco-net-compiler`

"Neco . . . takes a Petri net and builds a library that has all the primitives to explore the state space . . . optimised in many ways."

Future Work

Modelling

- user interface, software tool and case study,
- data integration with sources of data and conflict.

Conflict Detection

- model composition – adequacy of simplistic approach,
- conflict detection using logical specification and constraint solvers,
- scheduling constraints.

Conflict Resolution

- recommendation of minimal changes for conflict resolution,
- e.g. bypass activities,
- e.g. reschedule.

Thank you

Phil Weber

http://www.birmingham.ac.uk/mitcon/

http://www.cs.bham.ac.uk/~weberpy/
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