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

COPD overview

Person over 16 at risk of COPD

- Diagnosis and assessment
- Multidisciplinary team
- See what NICE says on patient experience

Management

- Managing exacerbations

Palliative care

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Two Problems

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

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**.

- **Implicit cycle** of retesting.
- What does **Metformin** conflict with?
- What does **HbA1c** interact with?
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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- models can be unstructured,
- especially the semantics w.r.t. data are unspecified.
Routing may be dependent on and modify data, e.g.

- Is patient already taking medication $m$?
- If test $X > v$, 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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Fragments of doctors’ appointments for review of

**OA** : Osteoarthritis.

**COPD** : Chronic Obstructive Pulmonary Disease (Lung Disease).
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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 \( E \subseteq N \times N \),
- \( N \in \{ \text{Start, Stop, Activity, Fork, Join, Decision, Merge} \} \),
- \( G \) 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** $T(x_i) \in \{T_1, \ldots, T_m\}$,
- **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. $\text{pre}(\text{a}) := c(x_1, \ldots, x_d) \triangleq (x_i > 55)$.
- **Activity may carry out** data modifications:
  - statement $f(\cdot) : V \rightarrow V'$ over variables in $X$,
  - e.g. $x := x + 1$ or $x := \text{False}$,
- 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:

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

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

- \( m : E \rightarrow \{ T_1, T_2, \ldots \} \) is a marking describing 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 \( V \rightarrow V' \).
BPMN\texttt{+V}: Execution Semantics

\textbf{e.g.} For an \textbf{Activity} \texttt{a} in a well-formed BPMN\texttt{+V} model:

- one input and one output sequence flow \texttt{e}_{in}, \texttt{e}_{out}.
- \texttt{a} consumes \texttt{T} = (\textbf{t}, \textbf{V}) from \texttt{e}_{in} and returns \texttt{T}′ = (\textbf{t}, \textbf{V}′) on \texttt{e}_{out},
- if \exists \texttt{T} = (\textbf{t}, \textbf{V}) \in \texttt{m(e}_{in}) \mid \textbf{pre}(\texttt{a}) \models \textbf{V}, \quad // \textbf{V} satisfies any pre-condition.
- then \texttt{m \xrightarrow{a} m′}, where

\begin{enumerate}
  \item \texttt{post(\texttt{a})} \models \textbf{V}′, and
  \item \texttt{m′(e)} =
    \begin{align*}
      m(e) \setminus \{T\} & \quad \text{if } e = e_{in}, \quad // \textbf{V}′ satisfies any post \text{ – condition}. \\
      m(e) \cup \{T′\} & \quad \text{if } e = e_{out}, \quad // \text{token is ‘moved’}. \\
      m(e) & \quad \text{otherwise}.
    \end{align*}
\end{enumerate}

\textbf{e.g.} \quad \texttt{pre(\texttt{a})} \quad := \quad \neg\text{NSAIDS}, \\
\texttt{f(\texttt{a})} \quad \triangleq \quad \text{corticosteroids} \quad := \quad \text{corticosteroids} + 1.

\begin{itemize}
  \item – Similarly for all node types.
\end{itemize}
BPMN+V: Data Annotation

**Data attributes**

- **guard**: execution dependency on data
- **data**: execution modifies data

**Managing a patient with stable COPD**

1. **Review core treatments**
   - Supply interventions to encourage weight loss
   - Consider addition of opioid analgesics. Consider risks and benefits, particularly in older people
   - No further pain relief required
   - Prescribe topical capsaicin
   - Prescribe paracetamol for pain relief
   - Do not offer rubefacients for treating osteoarthritis.

2. **Review non-pharmacological treatments**
   - End of core treatment review
   - Assess core treatments
   - Supply written information
   - Supply interventions to encourage weight loss
   - Agree exercise plan
   - Prescribe paracetamol for pain relief
   - Prescribe topical NSAIDs for pain relief
   - Review non-pharmacological treatments

3. **End of medication review**
   - Arrange plasma level monitoring
   - If yes, review medication
   - If no, continue with consultation
   - Review core treatment review
   - Review medication for the patient with COPD
   - Review corticosteroid usage and requirement
   - Review theophylline usage and requirement
   - Review theophylline after successful trial of short acting and long acting bronchodilators and patient tolerates inhaled therapy?
   - Prescribe Theophylline
   - Prescribe Mucolytics
   - Prescribe Roflumilast

4. **End of consultation**
   - Has the patient reported any breathlessness?
   - Why are Corticosteroids needed?
   - To manage an exacerbation
   - As maintenance in advanced COPD
   - Why are Theophylline needed?
   - To manage an exacerbation
   - As maintenance in advanced COPD
   - To manage an exacerbation
   - As maintenance in advanced COPD

**Data attributes**

- **INT**: NSAIDS, BOOL: breathless
- **guard**: NSAIDS<1, data: NSAIDS+1, guard: not breathless
- **Data attributes**
  - **data**: NSAIDS+1, guard: NSAIDS<1
  - **data**: not breathless

**Data attributes**

- **INT**: corticosteroids, INT: theophylline, INT: roflumilast, INT: age
- **guard**: corticosteroids<1, data: corticosteroids+1, guard: theophylline<1, data: theophylline+1, guard: roflumilast<1, guard: corticosteroids<1, guard: age>65, guard: age<=65

**Data attributes**

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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 $D$,
- 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 $C_r(x_1, \ldots, x_d) \triangleq \neg (x_i \land x_j)$.

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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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.
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 $y > 1$. 

Phil Weber (Birmingham)

Conflict Detection – Clinical Processes

ICSSP, Paris, 7th July 2017
State Space Approach to Conflict Detection

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3. annotate with constraints (potential conflicts, e.g. meds. dependencies),
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).
State Space Approach to Conflict Detection

Current process for conflict detection (evaluating 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 the 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

- **Core treatments**
  - Assessed OA and COPD
  - Refer for intra-articular injections
  - Consider addition of opioid analgesics. Consider risks and benefits, particularly in older people.
  - No further pain relief required
  - Prescribe topical capsaicin
  - Do not offer rubefacients for treating osteoarthritis.
  - Prescribe NSAIDs
  - Prescribe topical NSAIDs for pain relief
  - Refer for intra-articular injections
  - Prescribe NSAIDs

- **Non-pharmacological treatments**
  - End of core treatment review
  - Review core treatment
  - Assess core treatments
  - Supply written information
  - Supply interventions to encourage weight loss
  - Agree exercise plan
  - Prescribe paracetamol for pain relief
  - Prescribe theophylline after successful trial of short acting and long acting bronchodilators and patient tolerates inhaled therapy?
  - Review theophylline usage and requirement
  - Review corticosteroid usage and requirement
  - Review corticosteroids
  - As maintenance in advanced COPD
  - To manage an exacerbation
  - Why are corticosteroids needed?

- **Conflict detection**
  - Potential conflict
  - Potential inconsistency
  - Simple parallel composition

- **End of medication review**
  - Review medication for the patient with COPD
  - Arrange plasma level monitoring
  - If yes, review medication
  - If no, continue with consultation
  - Has the patient reported any breathlessness?
  - If yes, review medication for the patient with COPD
  - Review theophylline usage and requirement
  - Review corticosteroid usage and requirement
  - Review corticosteroids
  - As maintenance in advanced COPD
  - To manage an exacerbation
  - Why are corticosteroids needed?
  - To manage an exacerbation
  - Why are corticosteroids needed?

- **End of medication review**
  - Is the patient over 65?
  - Is the patient over 65?
  - (Yes) Prescribe prophylactics
  - (No) Monitor for signs of osteoporosis and prescribe prophylactics
  - Review non-pharmacological treatments.
  - Consider addition of opioid analgesics. Consider risks and benefits, particularly in older people.
  - No further pain relief required

- **End of core treatment review**
  - Review non-pharmacological treatments.
  - Consider addition of opioid analgesics. Consider risks and benefits, particularly in older people.
  - No further pain relief required

- **Potential inconsistency**
  - Explore all effective values

- ** 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.

   ![Diagram of artificial process fragments]

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

<table>
<thead>
<tr>
<th>Model</th>
<th>Activity</th>
<th>Data</th>
<th>Initial Data</th>
<th>Conflict Model</th>
<th>Conflict Activity</th>
<th>Conflict Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA</td>
<td>Agree exercise plan [¬breathless]</td>
<td>breathless=TRUE</td>
<td>breathless=TRUE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prescribe NSAIDs</td>
<td>NSAIDS=1</td>
<td>NSAIDS=1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COPD</td>
<td>Prescribe cortico. and keep ...</td>
<td>cortico.=1</td>
<td>cortico.=1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prescribe roflumilast [th.lline&lt; 1]</td>
<td>th.lline=1</td>
<td>th.lline=0</td>
<td>COPD</td>
<td>Prescribe roflumilast</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prescribe th.lline ... [rofl.&lt; 1]</td>
<td>rofl.=1</td>
<td>rofl.=0</td>
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<td>Prescribe th.lline after ... rofl.</td>
<td></td>
</tr>
<tr>
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<td>cortico.=1</td>
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<td></td>
</tr>
</tbody>
</table>

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

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.
Averages over 30 randomly generated models.

“SNAKES is a Python library that provides all the necessary to define and execute many sorts of Petri nets”.

“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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