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Seeking Improved CPN Tools Simulator Performance:

Evaluation of Modelling Strategies for an Army Maintenance Process

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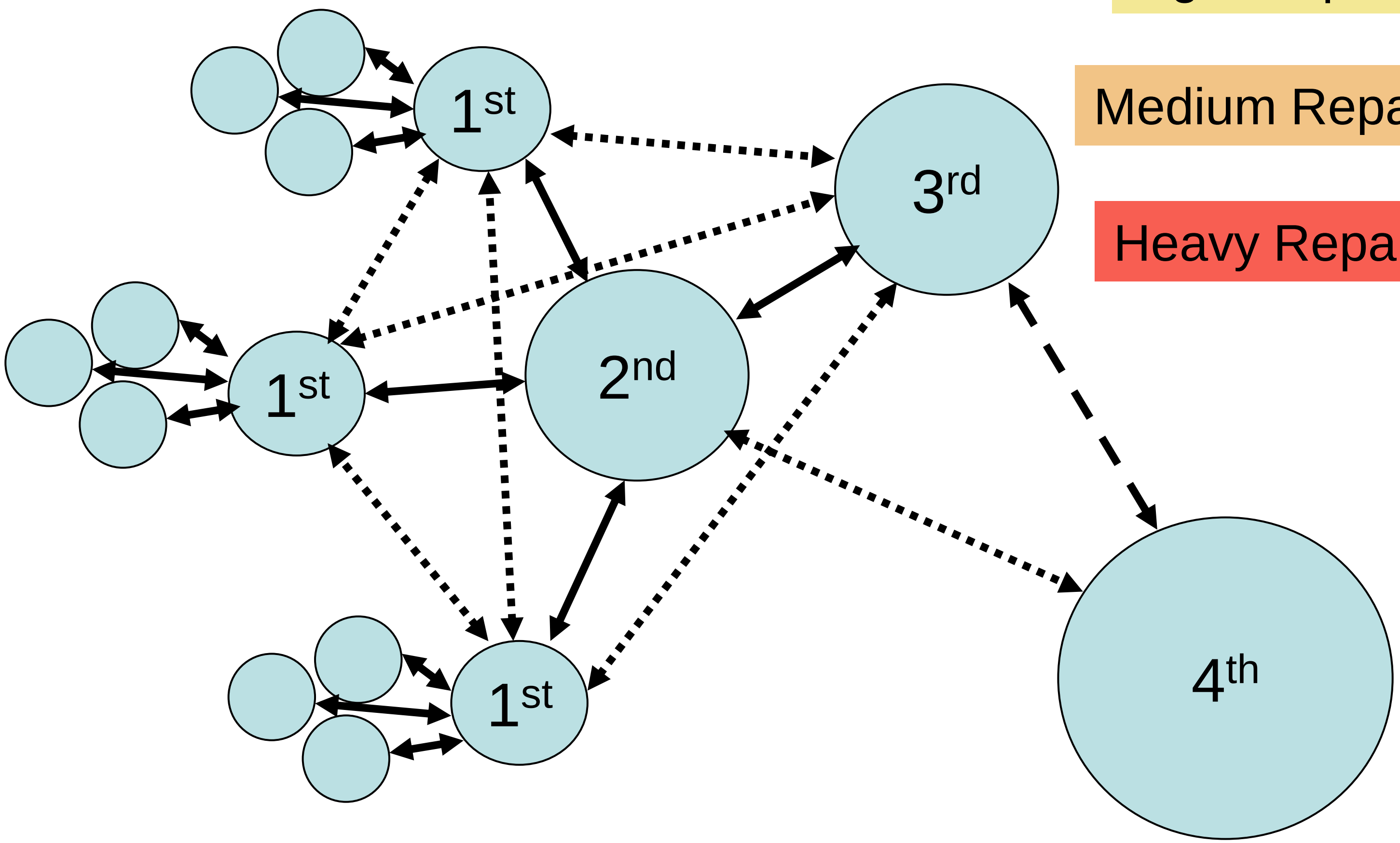
Australian Army is interested in Maintenance Planning

- **Example: Determine the composition of the maintenance workforce required to sustain a military operation**
  - determine the tasks and staff (by trade) required to maintain a given piece of equipment (maintenance liability)
  - given the inventory of equipment for the military operation, determine the number of tradespeople by trade required to sustain the operation
  - determine the distribution of the workforce over several workshops
- **Methods and Tool support that will allow them to:**
  - validate the feasibility of solutions
  - explore "what if" scenarios
  - optimize

This motivated our attempt to apply Timed Coloured Petri Nets and CPN Tools.

A Military Maintenance Network

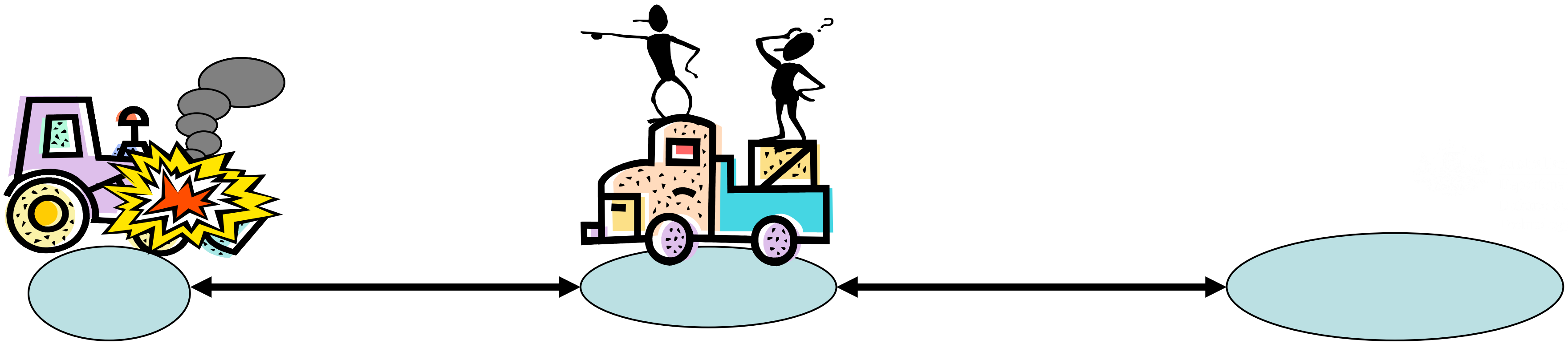


Light Repairs (1st and 2nd)

Medium Repairs (2nd and 3rd)

Heavy Repairs (3rd and 4th)

Maintenance Scenarios



When maintenance is required, there are five scenarios:

- **In-Situ: The equipment does not need to move from its current location.**
- **Self-Transport: Equipment moves itself to a suitable location.**
- **Distribution: Equipment is moved by a general transportation network.**
- **Recovery: A Recovery Team is sent from a workshop to recover the equipment and move it to a suitable location.**
- **Forward Repair: A Forward Repair Team comes to repair the equipment, and then returns to the workshop.**

If a maintenance workshop is full, the equipment and task is “backloaded” up the hierarchy of workshops.

A Defence Logistics Maintenance Process

System Components

- **Equipment (thousands)**
  - **Approx. 500-600 different item types**
    - Vehicles, weapons, plant, electronics etc.
  - **Maintenance**
    - preventative, servicing, wear, breakage, battle damage, inspections.
  - **Data (poorly captured)**
    - a combination of deterministic (scheduled) & random.

- **Tradespeople (hundreds)**
  - **Different trades – can only repair specific types, e.g.**
    - Vehicle Mechanic, Fitter Armaments, Electrician etc
  - **Non-productive time**
    - Picket duty, awaiting parts, sleep etc

- **Workshop/Maintenance System (tens of nodes)**
  - **1st – 4th line maintenance, Forward Repair Teams (FRT)**
  - **Backlog – maximum allowable work (hours)**
  - **Backloading – movement of equipment up a level**

Statistics

- 3 Levels of Hierarchy (plus one for initialisation)
- 27 places (88 place instances)
- 14 substitution transitions
- 44 executable transitions
- About 200 ML functions
- About 1600 lines of ML

Focus

- States of equipment during the maintenance cycle

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Timed Coloured Petri Net Model

Process Overview page

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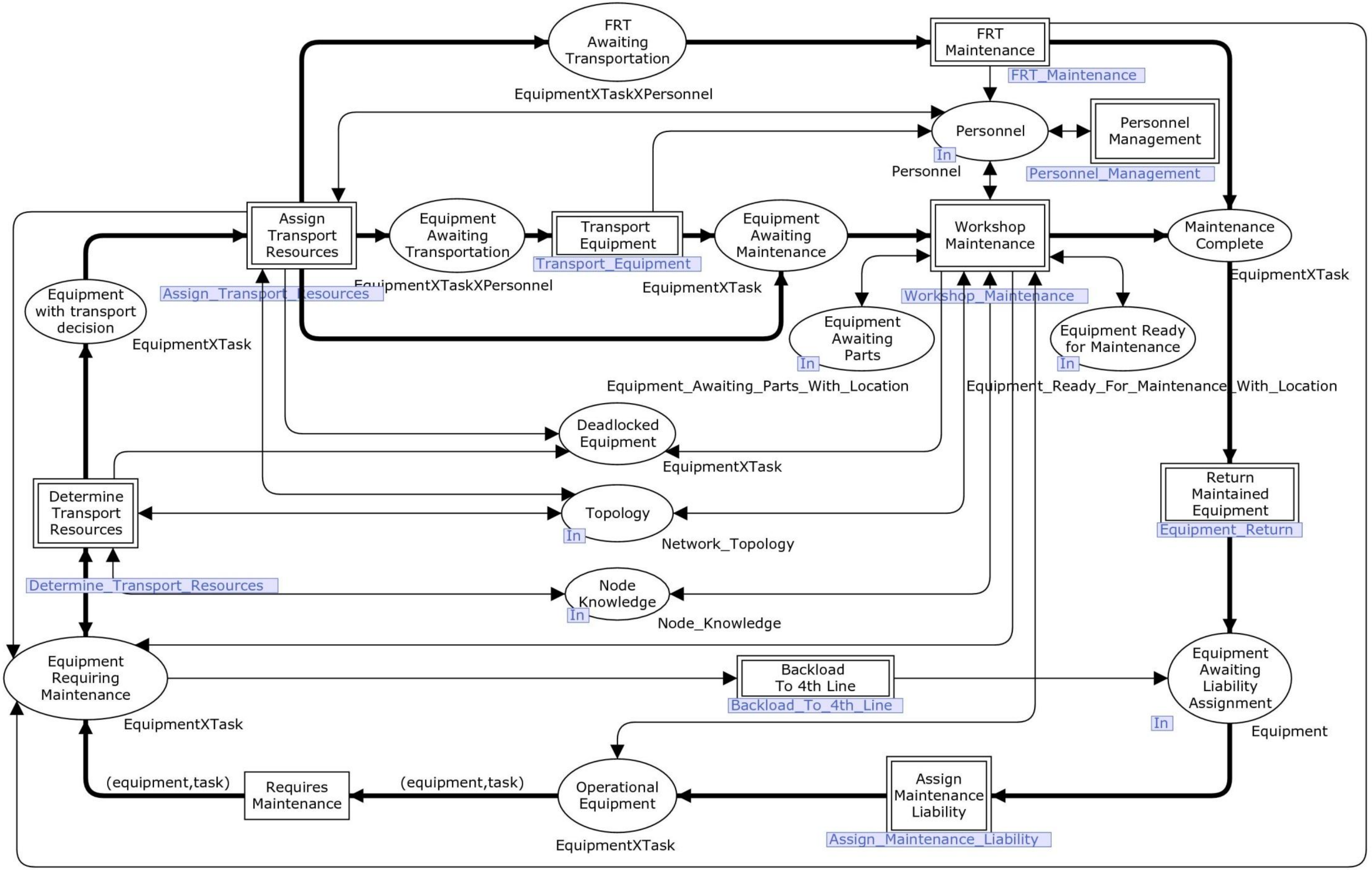

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Modelling Personnel as Tokens or in a List

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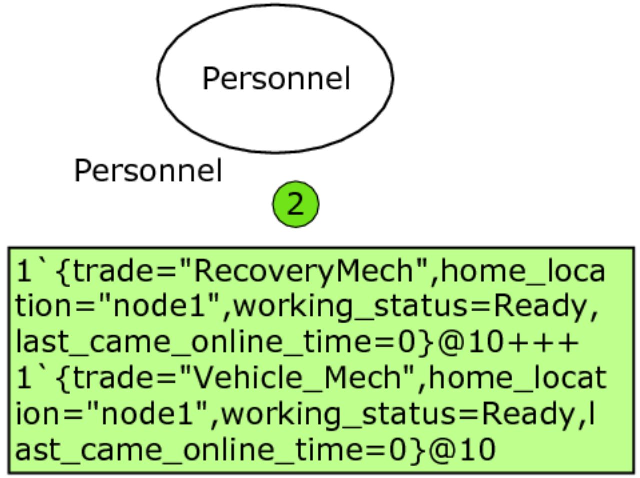
- **Each person as a token (Model 1):**

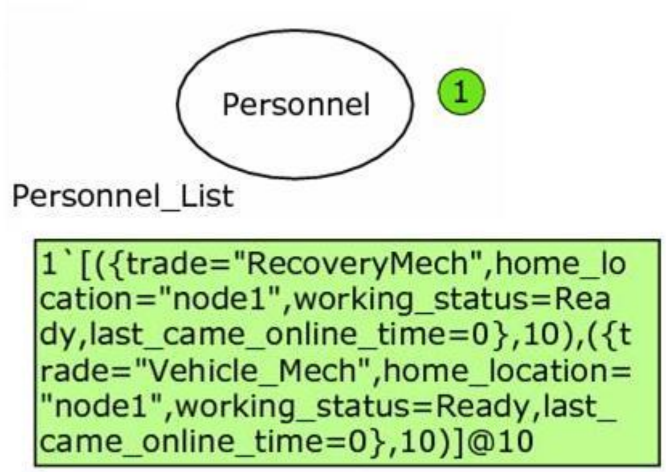
  colset Personnel = record
    trade : Trade *
    home_location : STRING *
    working_status : Personnel_States *
    last_came_online_time : INT timed;



- **Each person as a data value in a list (Model 4B):**

  colset Person = record
    trade : Trade *
    home_location : STRING *
    working_status : Personnel_States *
    last_came_online_time : INT;
  colset Personnel = product Person * INT;
  colset Personnel_List = list Personnel timed;

  - **Elements of list ordered by time value.**



Simulation Performance - Baseline

- **A baseline scenario:**
  - **Five simple nodes.**
  - **Two tradespeople at each node (10 in total):**
    - One Recovery Mechanic and one Vehicle Mechanic at each node.
  - **Two tasks requiring teams at each node (10 in total):**
    - One Recovery Team and one Forward Repair Team to be formed at each node.
    - Recovery Team comprises one Recovery Mechanic and one other of any trade.
    - FRT comprises one Vehicle Mechanic and one other of any trade.

- **Scaling the baseline scenario:**
  - **Three dimensions:**
    - Number of available personnel
    - Number of tasks requiring teams at each node
    - Number of nodes
  - **The first two are implemented using a *personnel multiplier* and a *team multiplier*:**
    - E.g. personnel multiplier of 2 gives 4 tradespeople per node (20 total)
  - **The third requires changes to model initialisation.**
    - Each node is as described in the baseline scenario (2 people, 2 tasks)

Simulation Performance - Tests

- **We performed five tests on both Model 1 and Model 4B using variants of the baseline scenario on the parts of the model previously identified as having performance concerns:**
  - **Moving personnel offline and online**
    - Allow personnel to move offline and online for 20 days of model time.
    - Record how long CPN Tools takes to complete each simulation.
    - **Test 1:** scale the number of available personnel.
    - **Test 2:** scale the number of nodes.
  - **Assigning Personnel to Teams**
    - Simulate until all teams have been formed.
    - To test only the mechanism for forming teams, each team that is formed is disbanded immediately, freeing up people for the formation of another team.
    - **Test 3:** scale the number of teams requiring personnel.
    - **Test 4:** scale the number of available personnel.
    - **Test 5:** scale the number of nodes.
- **These two parts of the model were considered in isolation.**
- **Repeated the above tests with topology represented in net structure rather than in data (unfolding network topology).**

Simulation Performance – Folded Models

Moving Personnel Offline and Online

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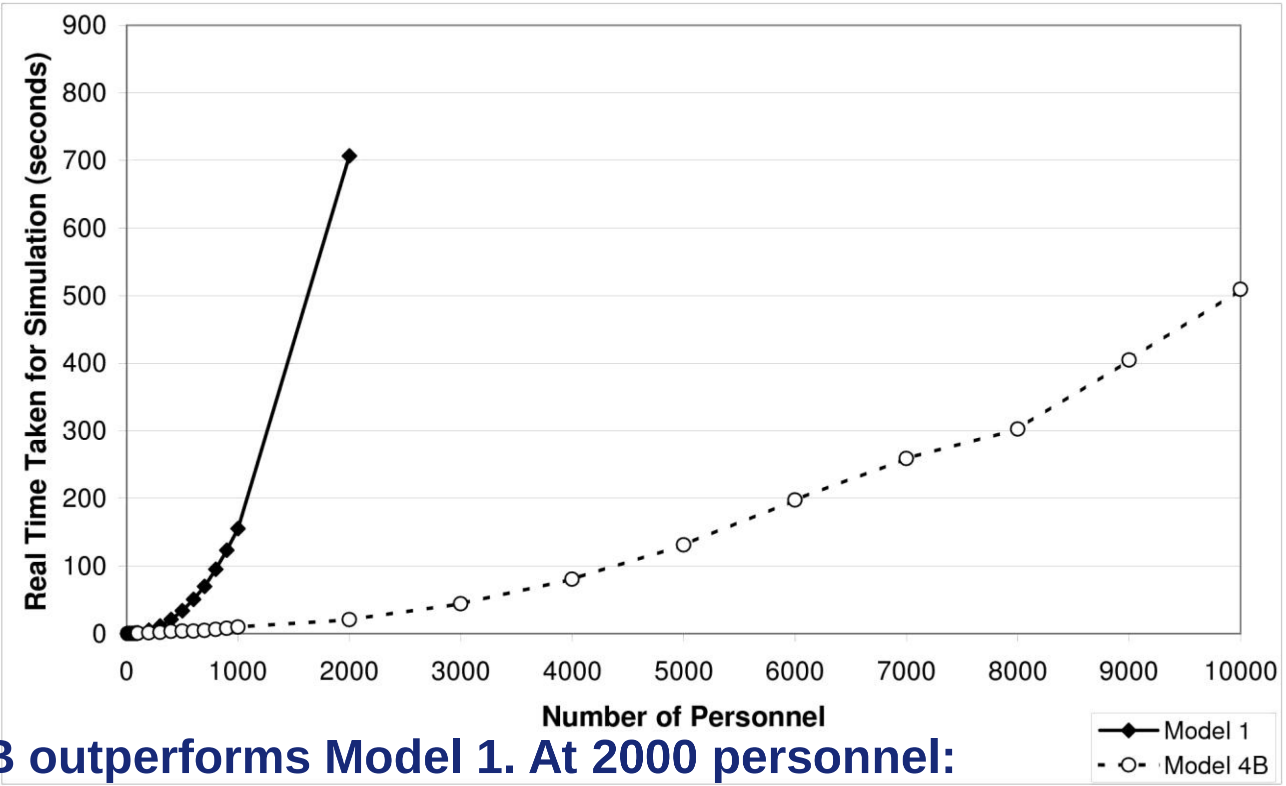
Test 1: Scaling personnel

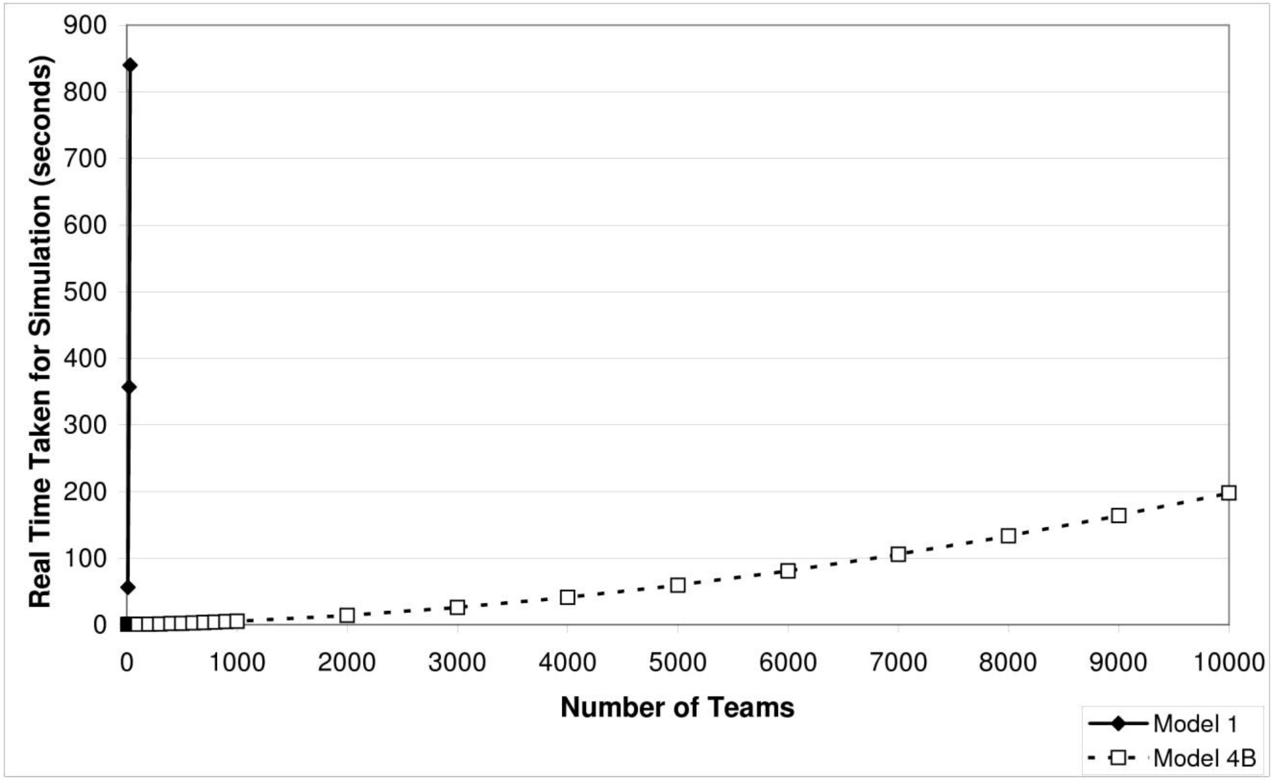


- **Model 4B outperforms Model 1. At 2000 personnel:**
  - **Model 1: 706.7 seconds**
  - **Model 4B: 20.5 seconds – a factor of 34 improvement**
  - **Due to finding enabled binding elements:**
    - **Model 4B has two list tokens (offline, ready) to choose from**
    - **Model 1 has a large multiset of people to choose from**
- **Test 2: (Scaling nodes) similar trend (see paper)**
  - **Personnel are geographically separate but reside on the same place in the model**

Simulation Performance – Folded Models

Assigning Personnel to Teams

Test 3: Scaling teams



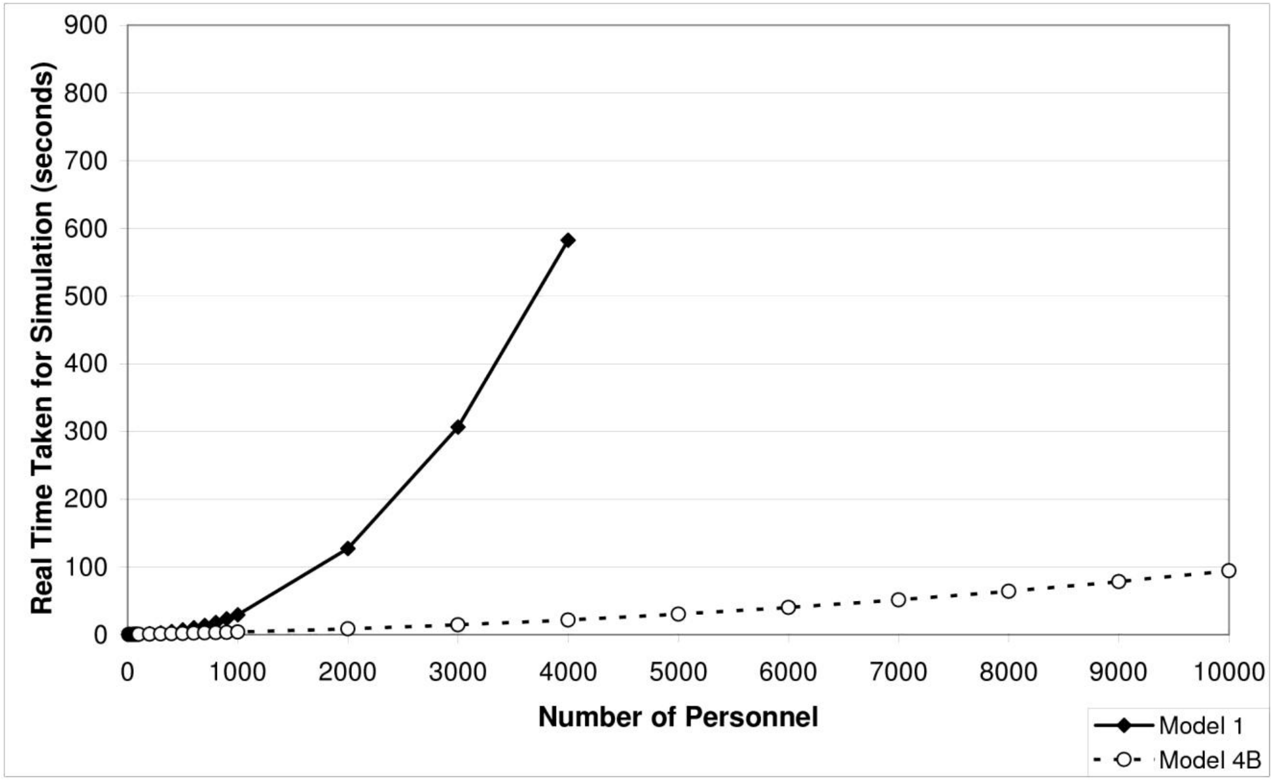
- **Model 4B far outperforms Model 1. At 30 teams:**
  - **Model 1: 839.9 seconds**
  - **Model 4B: 0.0625 seconds – a factor of 13400 improvement**
  - **Due to the inefficient workaround mechanism for selecting a varying number of partially specified people in Model 1.**

- **Tests 4 and 5: (scaling personnel and nodes) similar trends (see paper).**

Simulation Performance – Unfolded Models

Moving Personnel Offline and Online

Test 1U: Scaling personnel

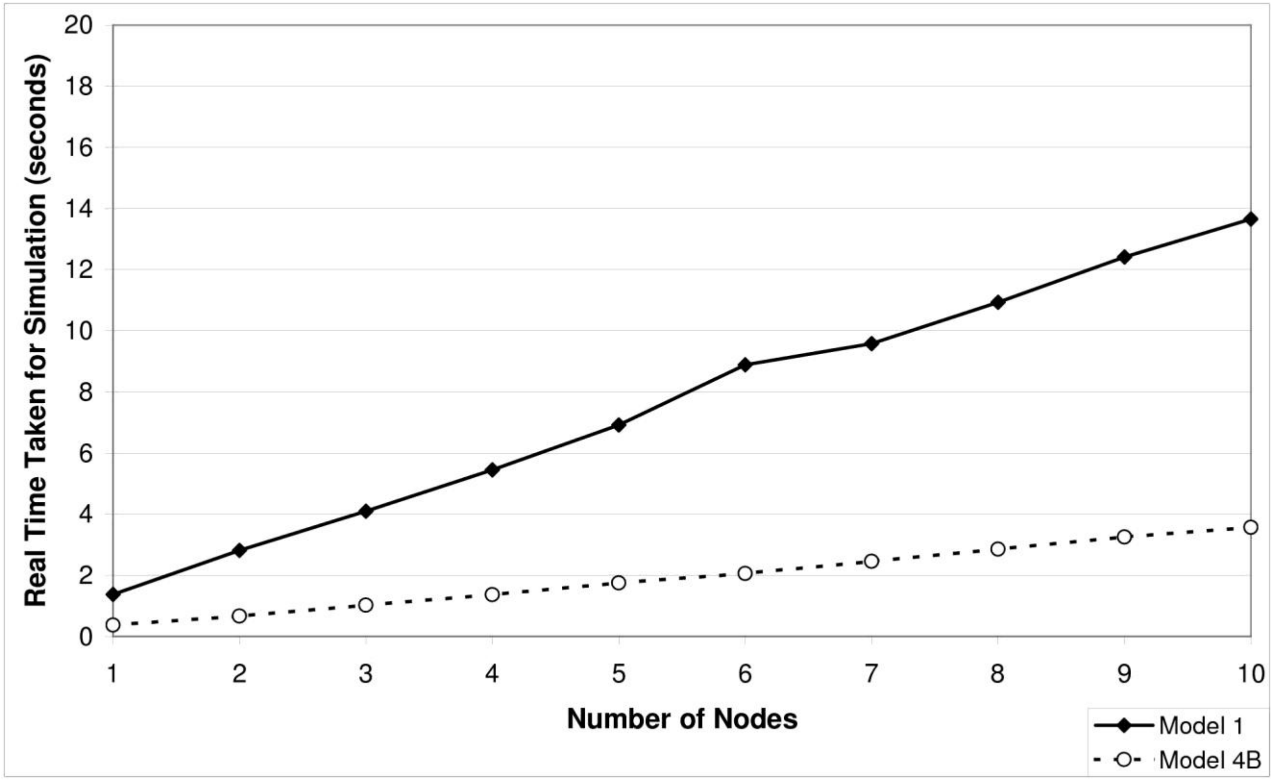


- **Model 4B is still better, both models benefit from unfolding the topology:**
  - **Model 1: a factor of 6 improvement at 2000 personnel.**
  - **Model 4B: a factor of 2.5 improvement at 2000 personnel.**
- **Possible reasons:**
  - **Simpler calculations when determining enabled binding elements**
  - **Less tokens to select from in Model 1 – the personnel tokens are distributed across multiple places.**

Simulation Performance – Unfolded Models

Moving Personnel Offline and Online

Test 2U: Scaling nodes



- For this plot the personnel multiplier is 50, to differentiate the results.
- This test reveals a major benefit to unfolding the network topology:
- Time taken appears to scale linearly with the number of nodes.
  - Previously, increasing the number of nodes increased the number of people in the Personnel place.
  - Now, the same number of people (2*50) are in the Personnel place of each node.
  - Duplicating the net structure essentially duplicates the calculations involved.

Simulation Performance – Unfolded Models

Assigning Personnel to Teams

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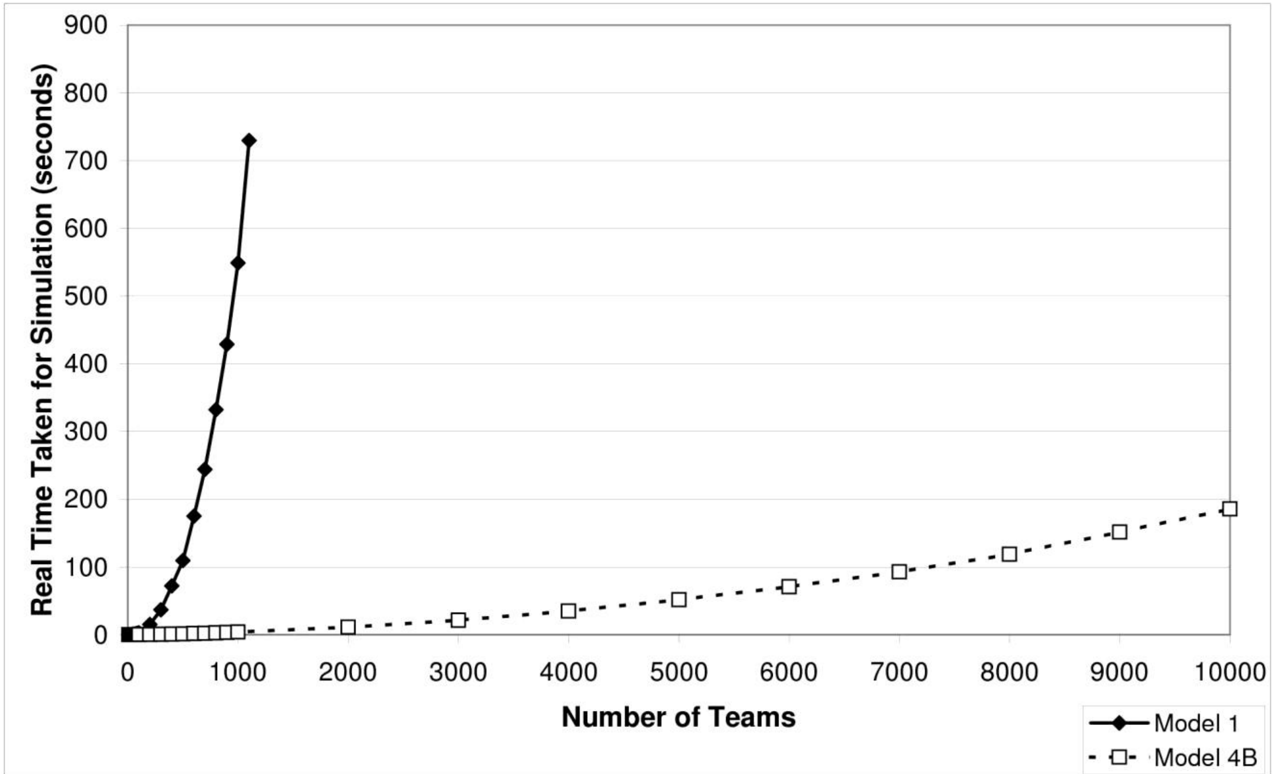
Test 3^U: Scaling teams

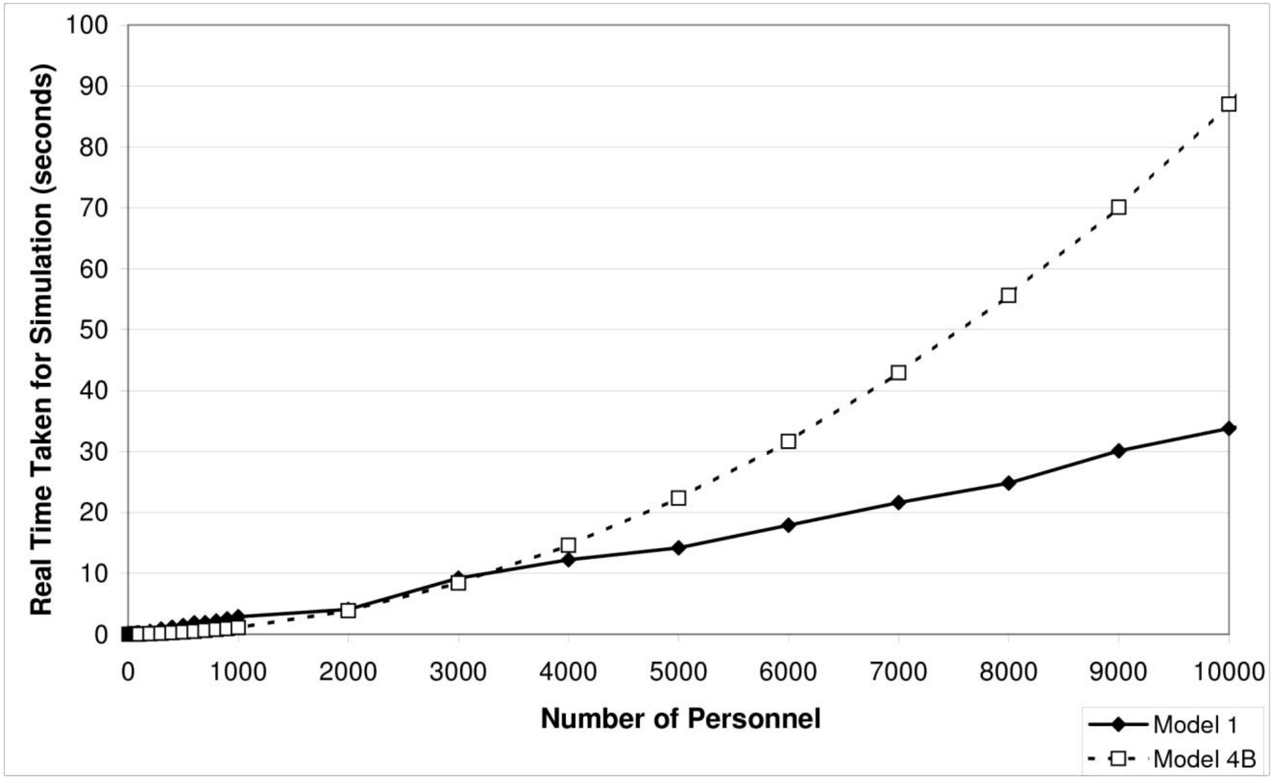


- **Model 4B: only marginal improvement with an unfolded topology.**
- **Model 1: significant improvement (but still much worse than Model 4B)**
    - **Folded topology: Model 1 took 840 seconds to assign people to 30 teams.**
    - **Unfolded topology: Model 1 takes 730 seconds to assign people to 1100 teams.**
- **Improvement in Model 1:**
    - **No. of tokens in any one place are reduced (now distributed over multiple places)**
    - **The effect of this is more pronounced in Model 1 due to its inefficient "workaround" selection mechanism.**

Simulation Performance – Unfolded Models

Assigning Personnel to Teams

Test 4^U: Scaling personnel

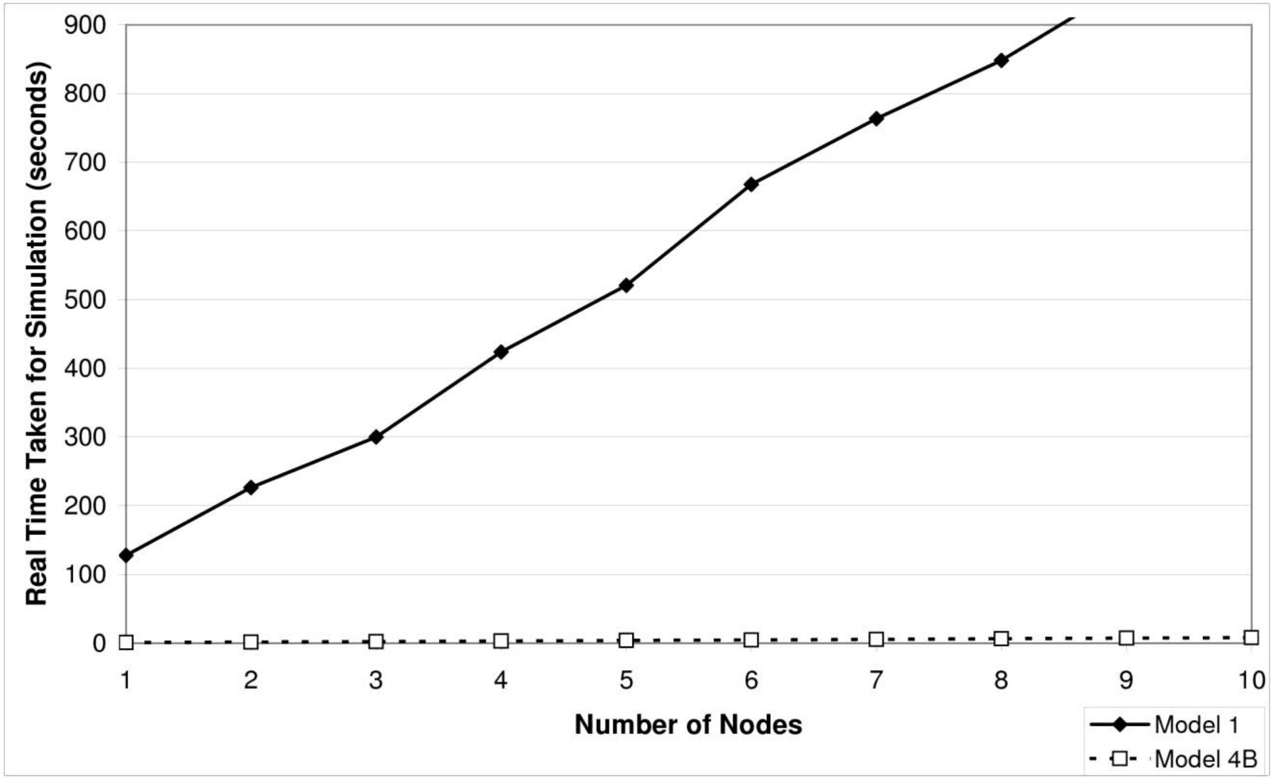


- **Model 1 outperforms 4B! and appears to scale linearly:**
  - **Experiments to 100,000 people (not shown) further indicate a linear relationship**
  - **Model 1 increasingly outperforms Model 4B.**
- **Reasons: We suspect that the selection mechanism in Model 1:**
  - **Is highly sensitive to the number of distinct personnel tokens to choose from.**
  - **Is relatively independent of the multiplicity of the distinct tokens.**
- **Whereas Model 4B's list manipulations depend on the length of the lists involved, which increase regardless of a folded or unfolded topology.**

Simulation Performance – Unfolded Models

Assigning Personnel to Teams

Test 5[U]: Scaling nodes



- **Note that here the team multiplier is 100, to differentiate the results.**
- **Both now appear to scale linearly in the number of nodes.**
  - **Expected, as duplicating net structure duplicates the calculations involved.**
- **Model 4B still wins, but Model 1 benefits more from unfolding:**
  - **Model 1 with two nodes:**
    - **Folded Model 1 took over 1.5 hours, unfolded Model 1 took under 4 minutes (225 seconds)**
  - **Model 4B has also improved, but not by as much (factor of 1.68 at 10 nodes)**

Discussion

- **Model design for good model performance is difficult!**
- **Complex interactions between personnel and tasks resulted in a prohibitively large number of calculations to determine enabled binding elements in Model 1. This was greatly reduced in Model 4B.**
- **A folded network topology:**
  - **Modelling people as individual tokens results in inefficient simulations.**
  - **List-based representation is computationally superior without losing much of the desired behaviour of the model.**
- **An unfolded network topology:**
  - **Model 1 benefits the most, by distributing tokens over multiple places.**
  - **Model 4B also benefits, but to a lesser degree.**
- **Unfolding other aspects of the model:**
  - **This may provide additional performance gains.**
  - **However there comes a point when the model becomes unmanageable.**
  - **Unfolding reduces model flexibility, e.g. a new model must be produced for each new topology to be considered.**

Conclusions

- We have explored different modelling approaches to improve the simulation performance of an industrial-scale CPN model capturing the Australian Army's maintenance process.
  - Our aim: to improve simulation performance to a level that allows timely evaluation of different maintenance scenarios.
- Maintenance involves hundreds of personnel and thousands of pieces of equipment distributed over tens of locations.
  - Our original model did not allow any simulation results of a realistic scenario to be obtained. The simulation never proceeded past formation of the first team.
  - Profiling of the model revealed performance bottlenecks:
    - The "less-than" function for the Personnel colour set was being executed billions of times during the checking of enabling of the two transitions that form teams.
  - Exploring different data structures for personnel has resulted in dramatic performance gains by using lists of personnel, rather than the more natural use of multisets.
  - Considering models that do not encode the network topology of the maintenance system (i.e. partially unfolded models) has also shown promise.

Future Work

- These tests purposely cover extreme values of personnel, teams, and nodes, to elicit performance trends.
- Model 4B provides acceptable performance when considering cycling of personnel and assignment to teams in isolation.
  - When considering the model as a whole, this may not be the case.
  - Currently under investigation.
- We also would like to investigate a method of modelling personnel changing state from online to offline, and vice versa, that does not involve explicit transition occurrences.
- It is likely that these performance issues affect many industrial-scale CPN models:
  - A more fundamental understanding of the relationship between the use of various modelling constructs and their impact on analysis and simulation performance in CPN Tools will benefit the user community.
  - We hope that our work provides a starting point for the development of a set of guidelines for modelling complex systems that are more readily simulated by CPN Tools.