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16th World Congress on Engineering Asset Management (WCEAM 22)

5-7 October 2022

Seville

Models to Support Decision Making in Railway Infrastructure Asset Management

Professor John Andrews

Network Rail – Strategic University Partner in IAM

- Appointed Royal Academy of Engineering and Network Rail Professor of Infrastructure Asset Management - 2009
- Develop a Centre of Excellence in Asset Management
  - Develop models to support future asset management decision making.
  - Not restricted to railway research – taking best practice from other industries.

Aero

Submarines

Areas of Asset Management Modelling Research

Asset Models

- Future modelling approaches for asset Whole Life Cost models
- Renewal prediction modelling
  - Asset is replaced when maintenance becomes ineffective or too costly
- Resilience to climate change
  - Prevention of track buckling in long periods of hot weather

Route Models

- Route asset management
  - Linking the asset models to form a route model – system of systems
  - Common possession periods
- Establishing a fault tolerant railway
  - Design – partial redundancy
  - – strategic positioning of switches
  - Operation – bi-directional traffic management to move trains around a problem
  - Maintenance – slow track maintained to fast standards
  - – location of the maintenance response units
- Resilience to climate change - flooding

Asset Diversity – UK Railway Network

- Track (32,300 km)
  - Jointed and CWR
  - Ballast and sleepers
- Switches & Crossings (24,500)
- Drainage
- Electrification(40% of network)
  - Overhead line (2/3)
  - Conductor rail (1/3)

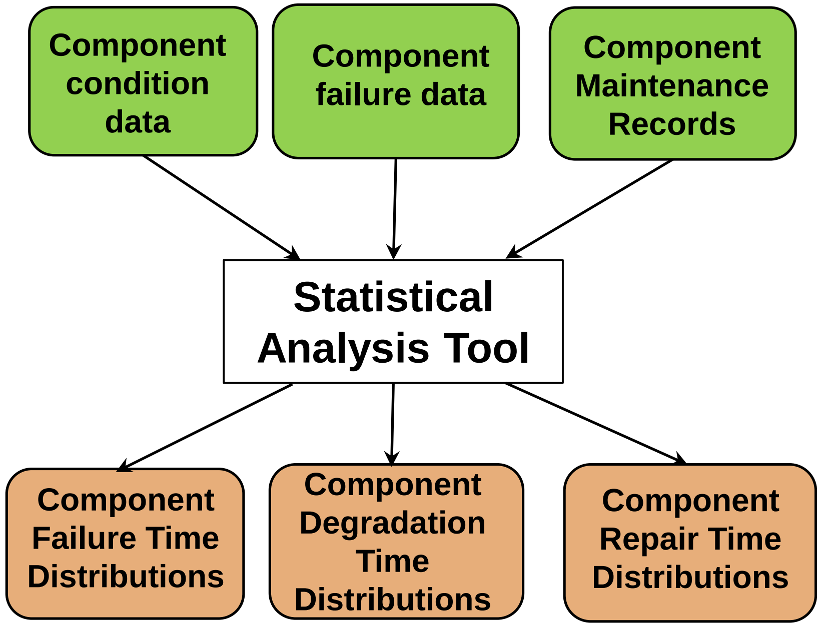
- Signalling Systems
  - Signalling control (858)
  - Interlocking
  - Train detection
  - Train protection
  - Signals and indicators (40,000)
  - Points operating equipment
  - Level crossings (6,800)
- Telecoms

Asset Diversity – UK Railway Network

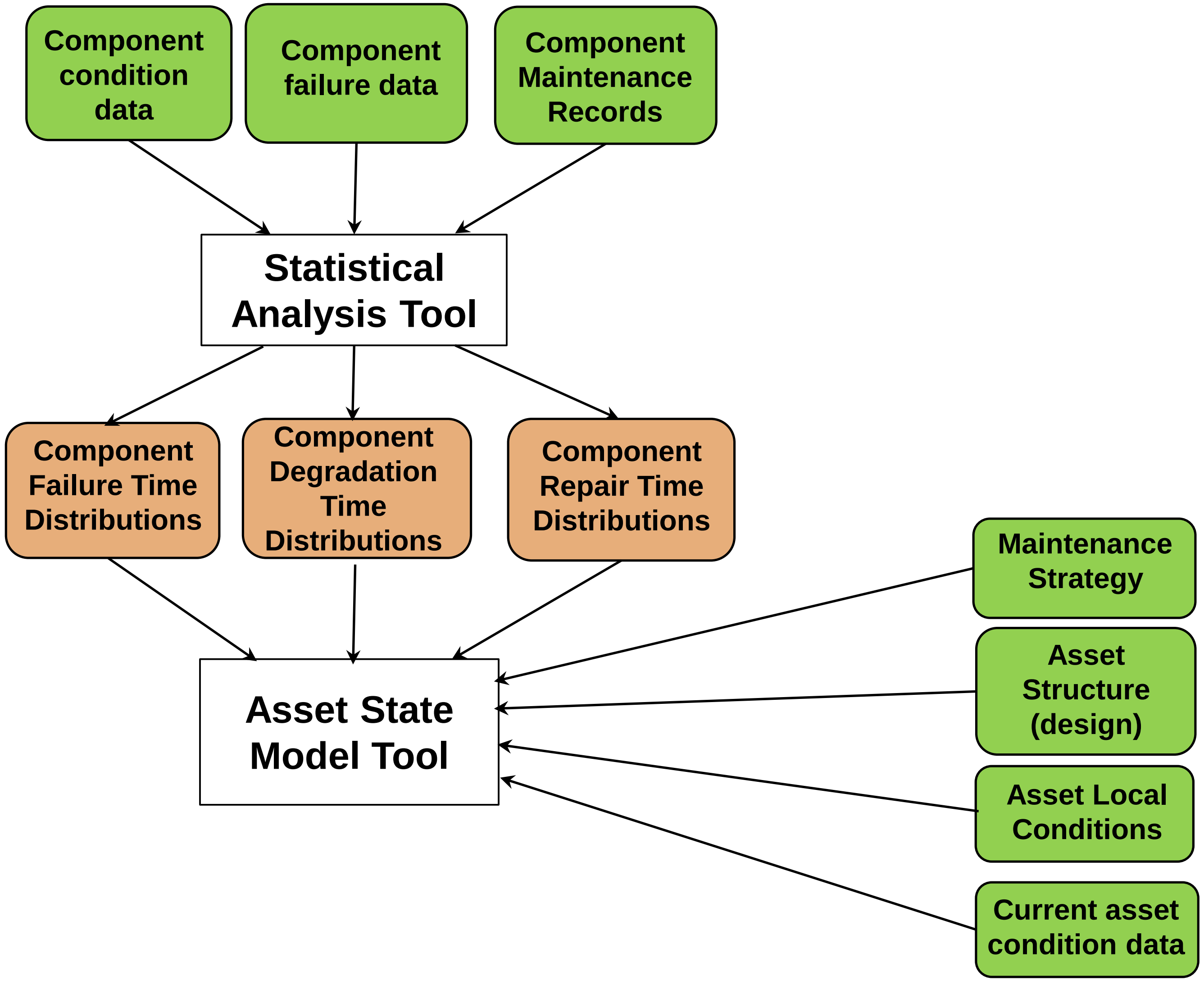
- Bridges (29,900)
  - 19,400 underline bridges
  - 9,100 overline bridges
  - 1,368 footbridges
    - Brick (50%)
    - Masonry (3%)
    - Stone (10%)
    - Concrete (12%)
    - Steel (18%)
    - Wrought Iron (7%)
  - 34 Unique Major Structures
    - Forth bridge
    - Tay Bridge
    - Esk Viaduct

- Tunnels (625 / 335 km)
- Retaining Walls (21,000)
- Coastal and River Defences (515)
- Stations (2,500)
  - 18 Major

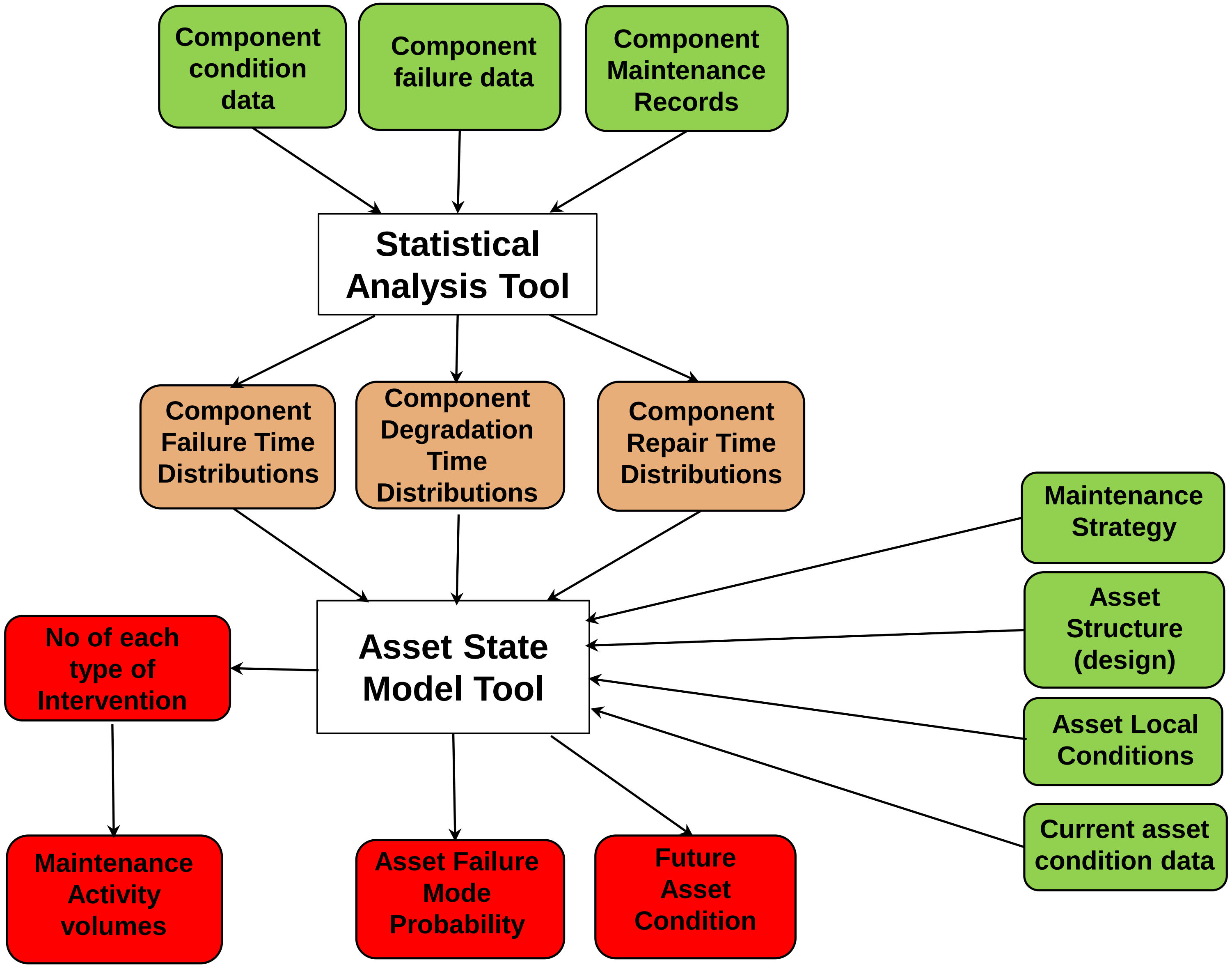
Asset Management Modelling Framework



Asset Management Modelling Framework



Asset Management Modelling Framework



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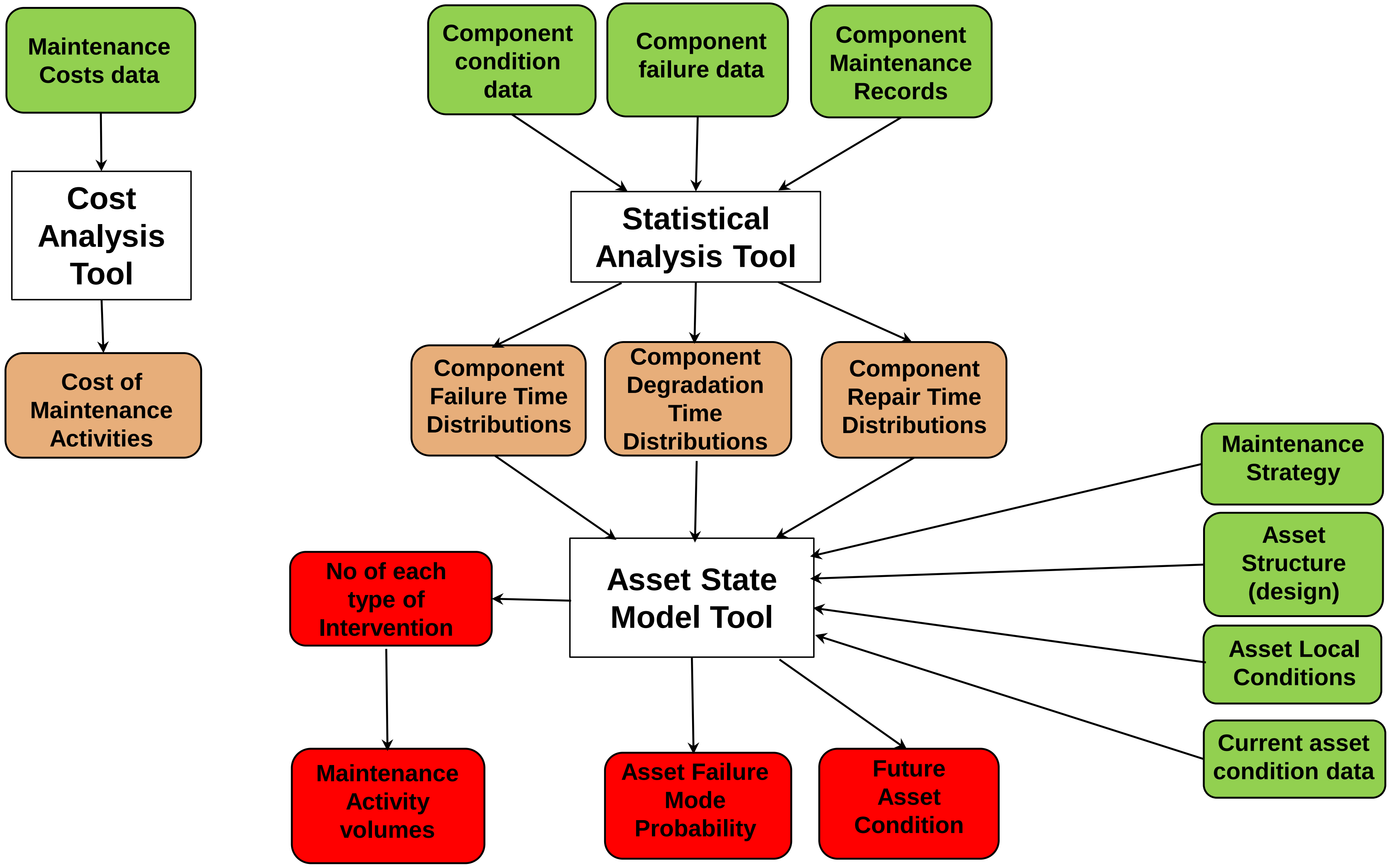

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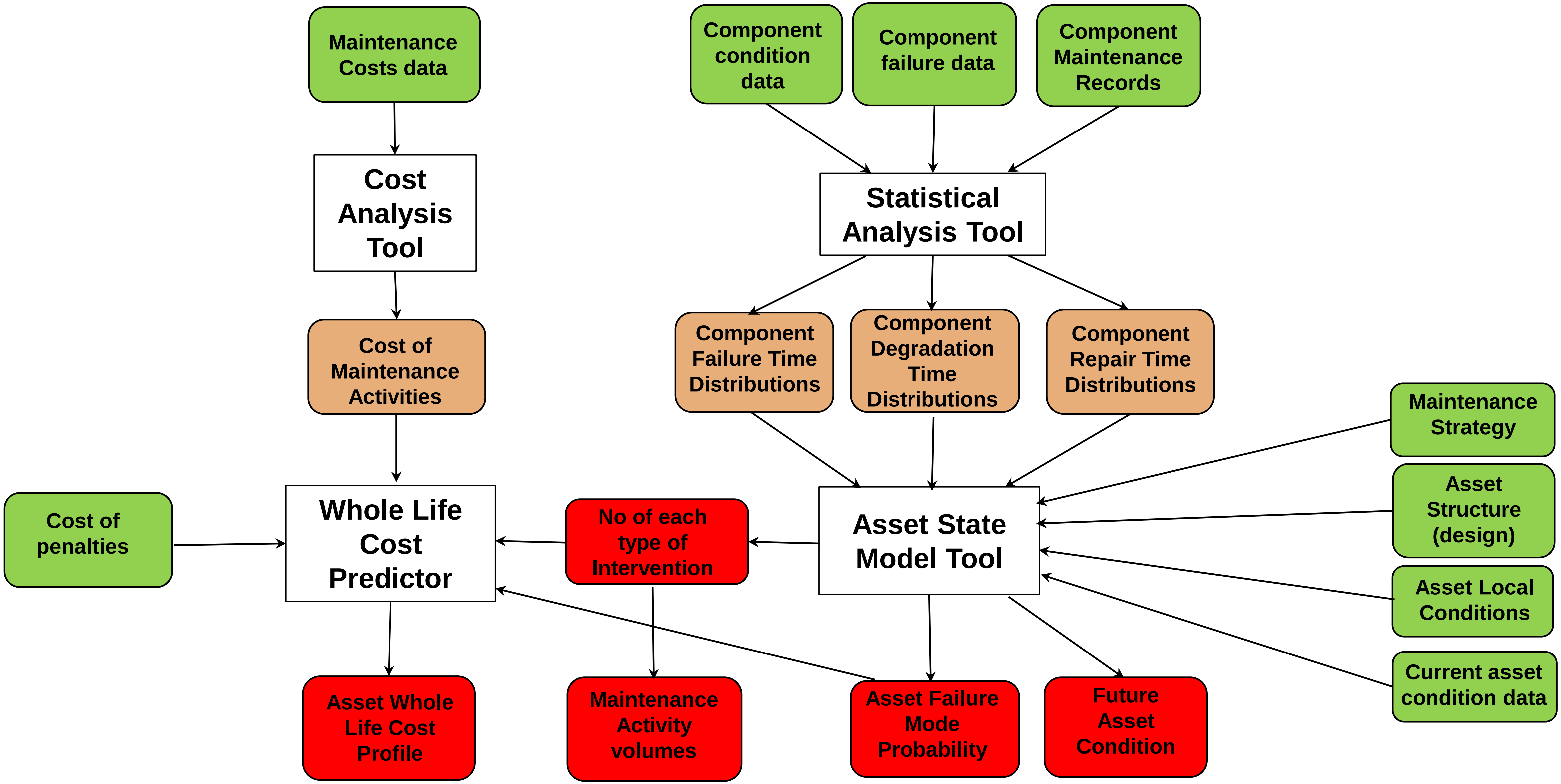
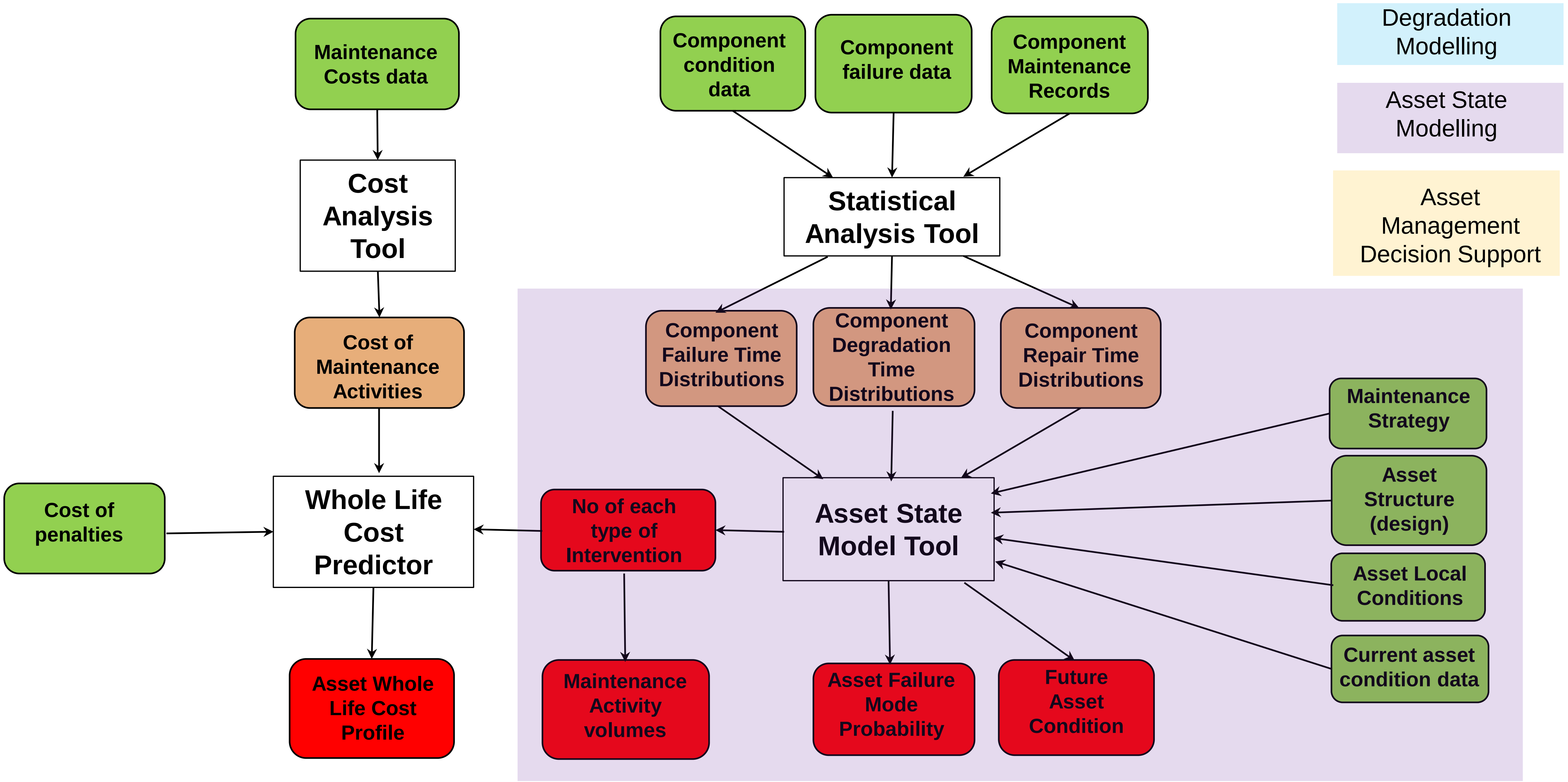


Asset Management Modelling Framework



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Exploring the features of the modelling methods

Markov / Petri Net

Track Geometry

Degradation (measured)

- Vertical alignment
- Horizontal alignment
- Gauge
- Cyclic top
- Twist

Inspection

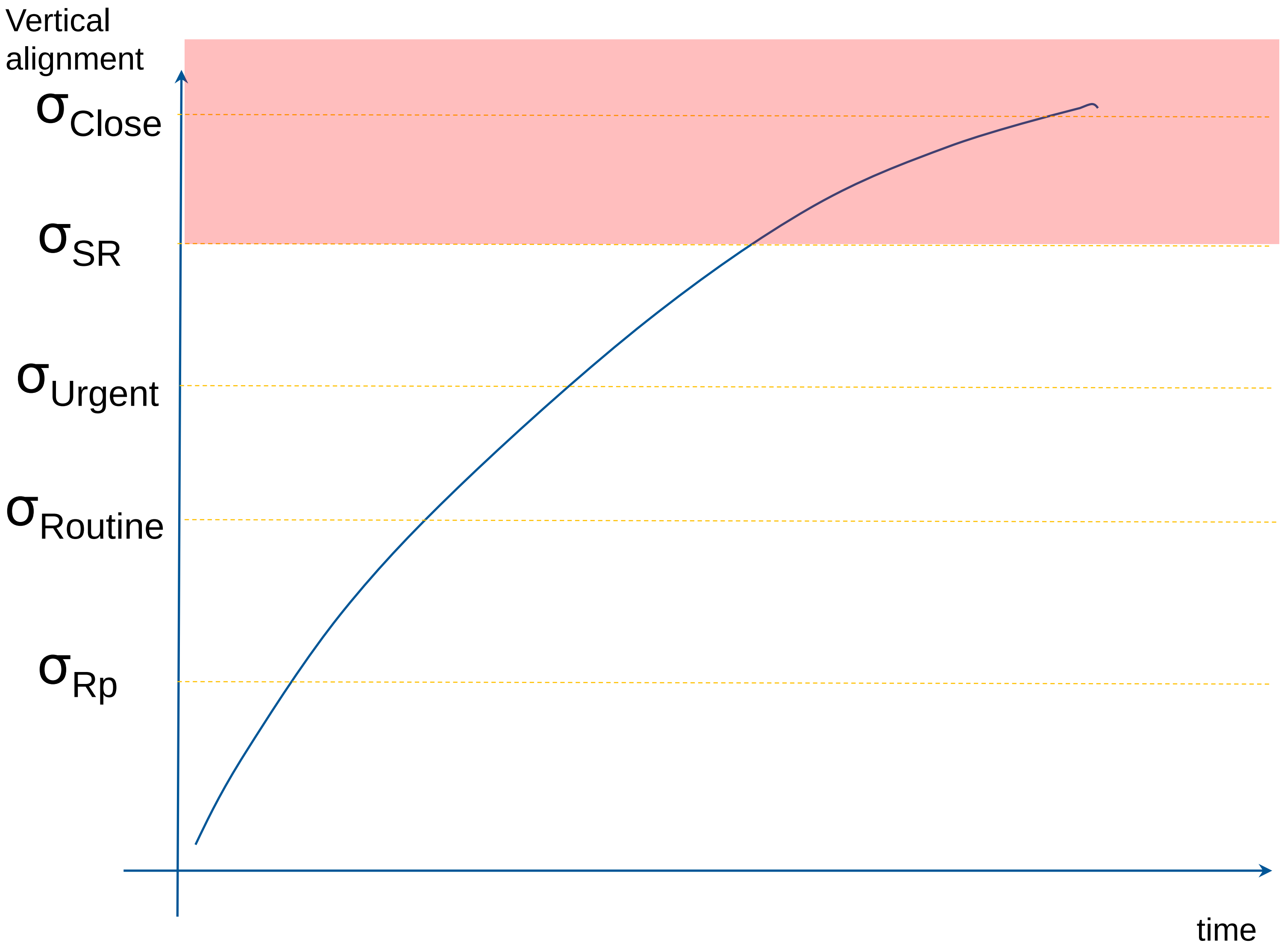
Recording Train

Intervention

Tamping

(rate of degradation depends on tamping history)

Vertical Alignment Degradation (200 m section)



LC	Line Closure / emergency maintenance
SR	Speed Restriction / emergency maintenance
UM	Urgent Maintenance
PO	Poor Condition / Routine Maintenance
RP	Repaired State
GD	Good Condition

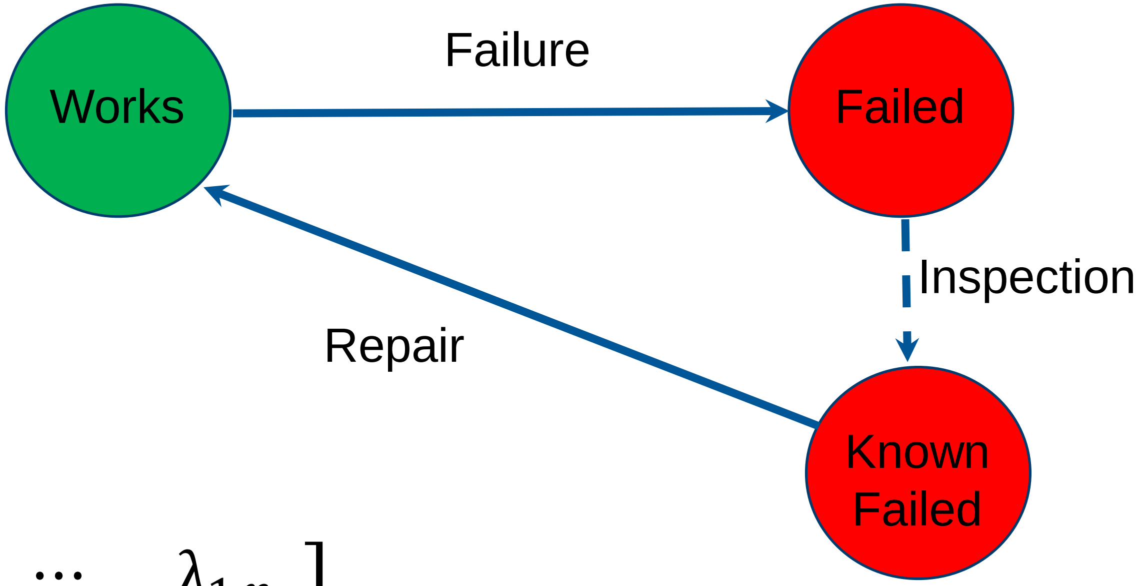
Markov Model

(1906)

Markov Analysis

Characteristics

- State-based method
  - states reflect the system condition
  - transitions cause change of state
- Memoryless property
- Constant rates of transition (exponential distribution for residence times)



$$(\dot{P}_1, \dot{P}_2, \ldots\ldots, \dot{P}_n) = (P_1, P_2, \ldots\ldots, P_n)\begin{bmatrix} -\lambda_{1,1} & \cdots & \lambda_{1,n} \\ \vdots & \ddots & \vdots \\ \lambda_{n,1} & \cdots & -\lambda_{n,n} \end{bmatrix}$$

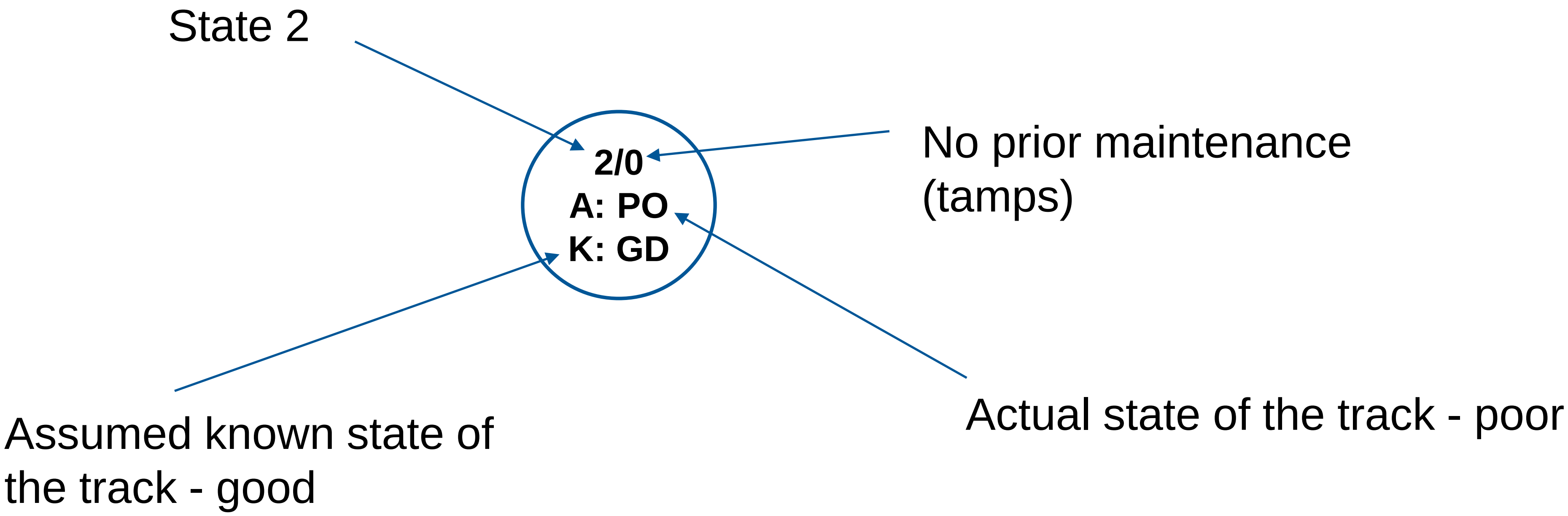
Solution

- Numerical Methods

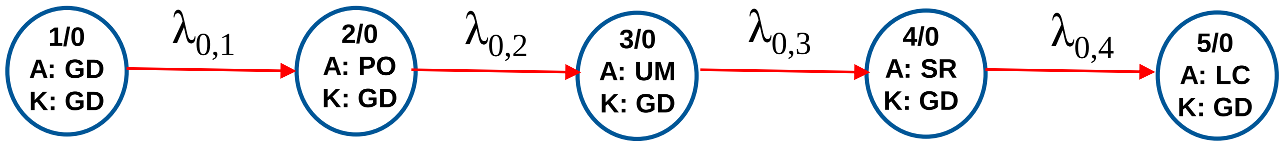
Outputs

- The probability of being in any state at any time

Track Geometry Markov Model –state definitions

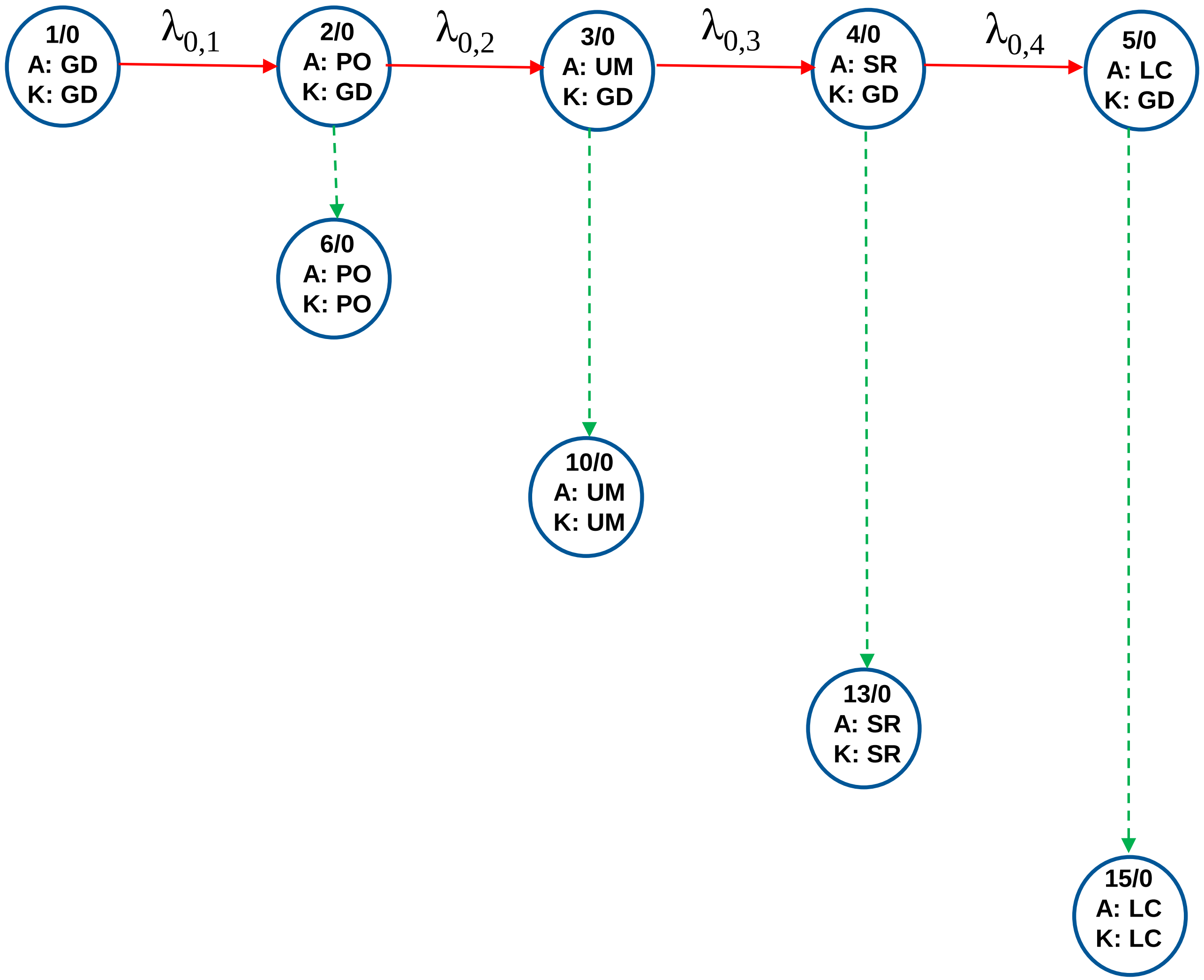


Track Geometry Markov Model



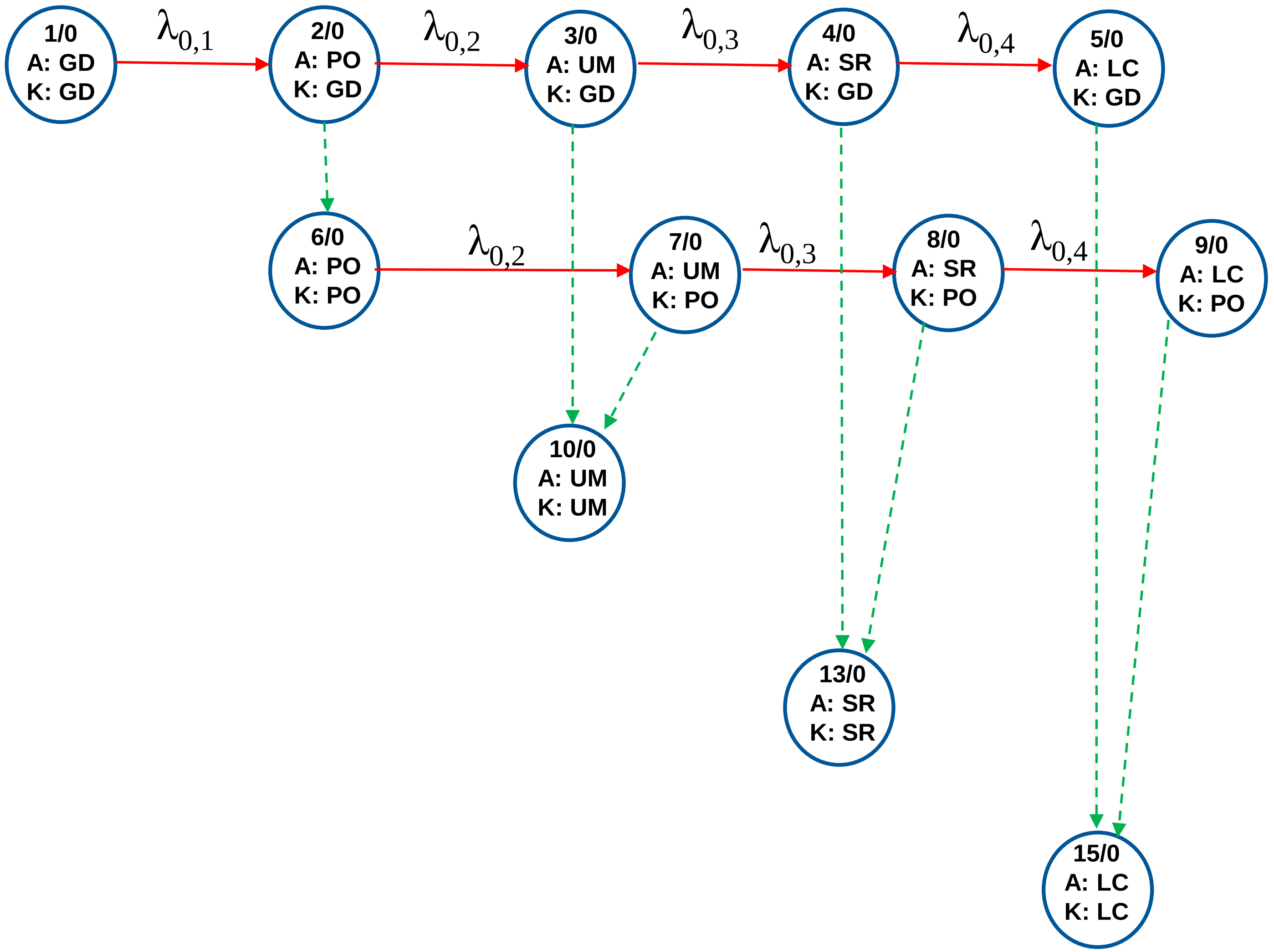
Degradation

Track Geometry Markov Model



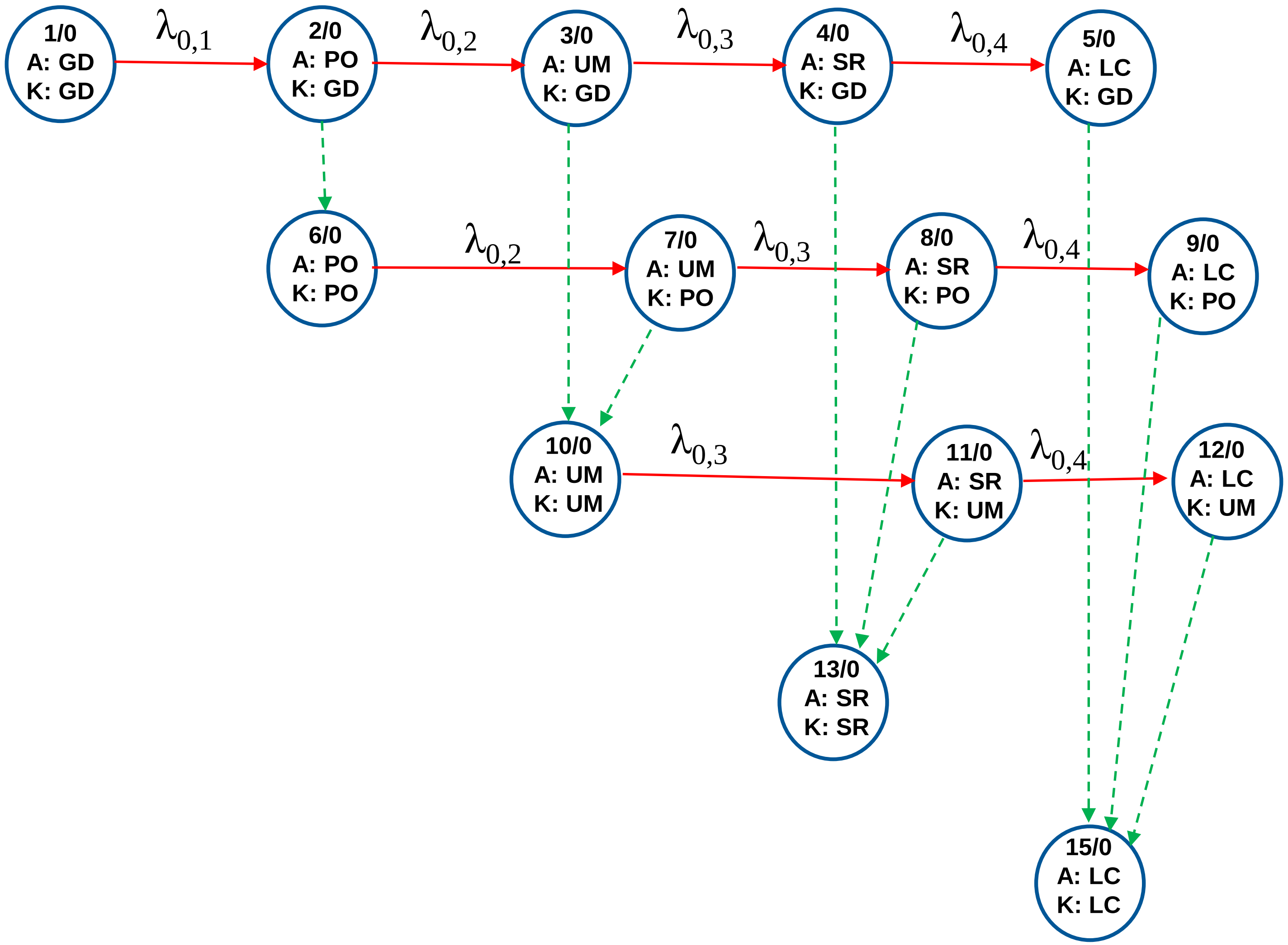
Inspection

Track Geometry Markov Model



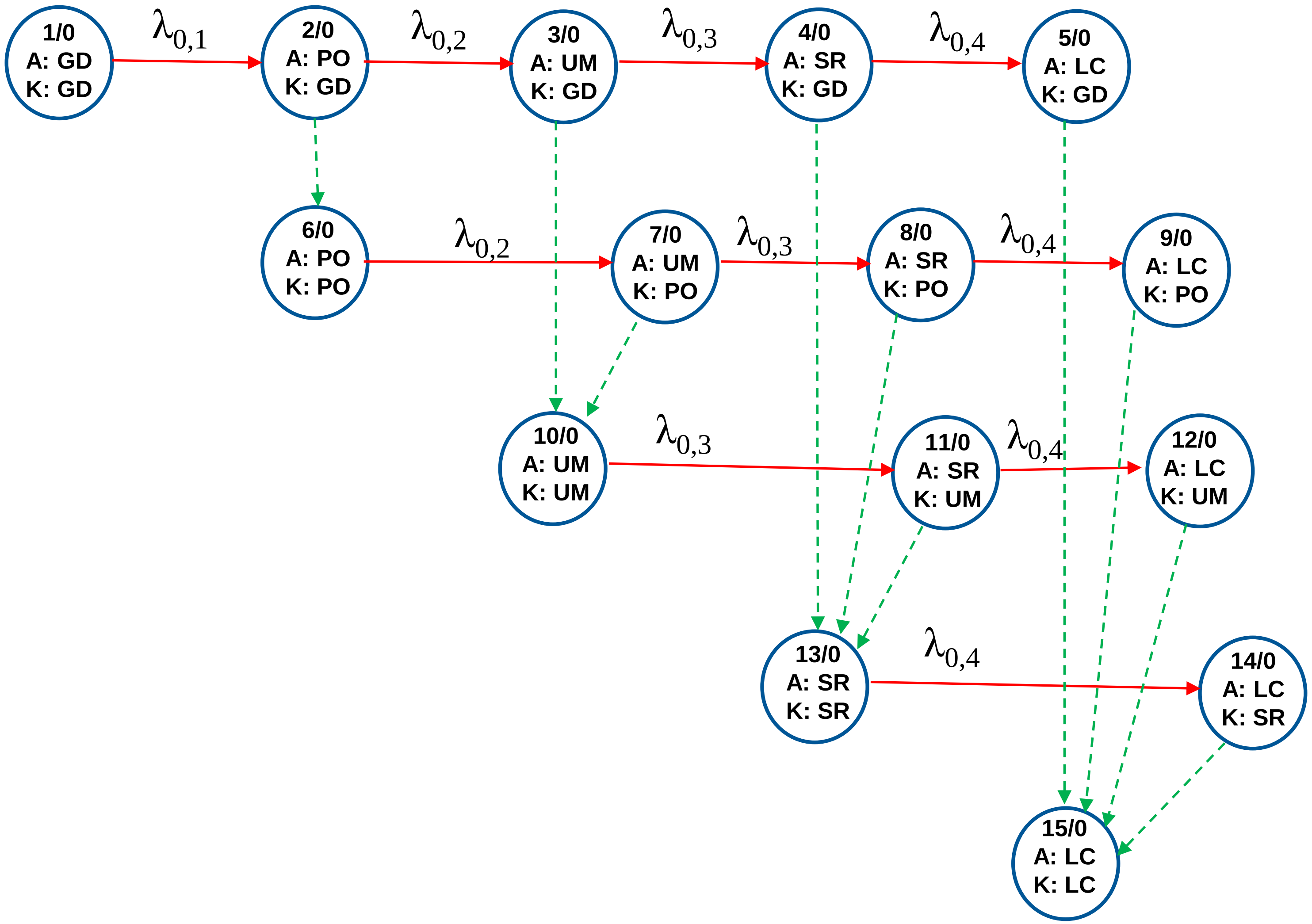
Degradation / Inspection

Track Geometry Markov Model



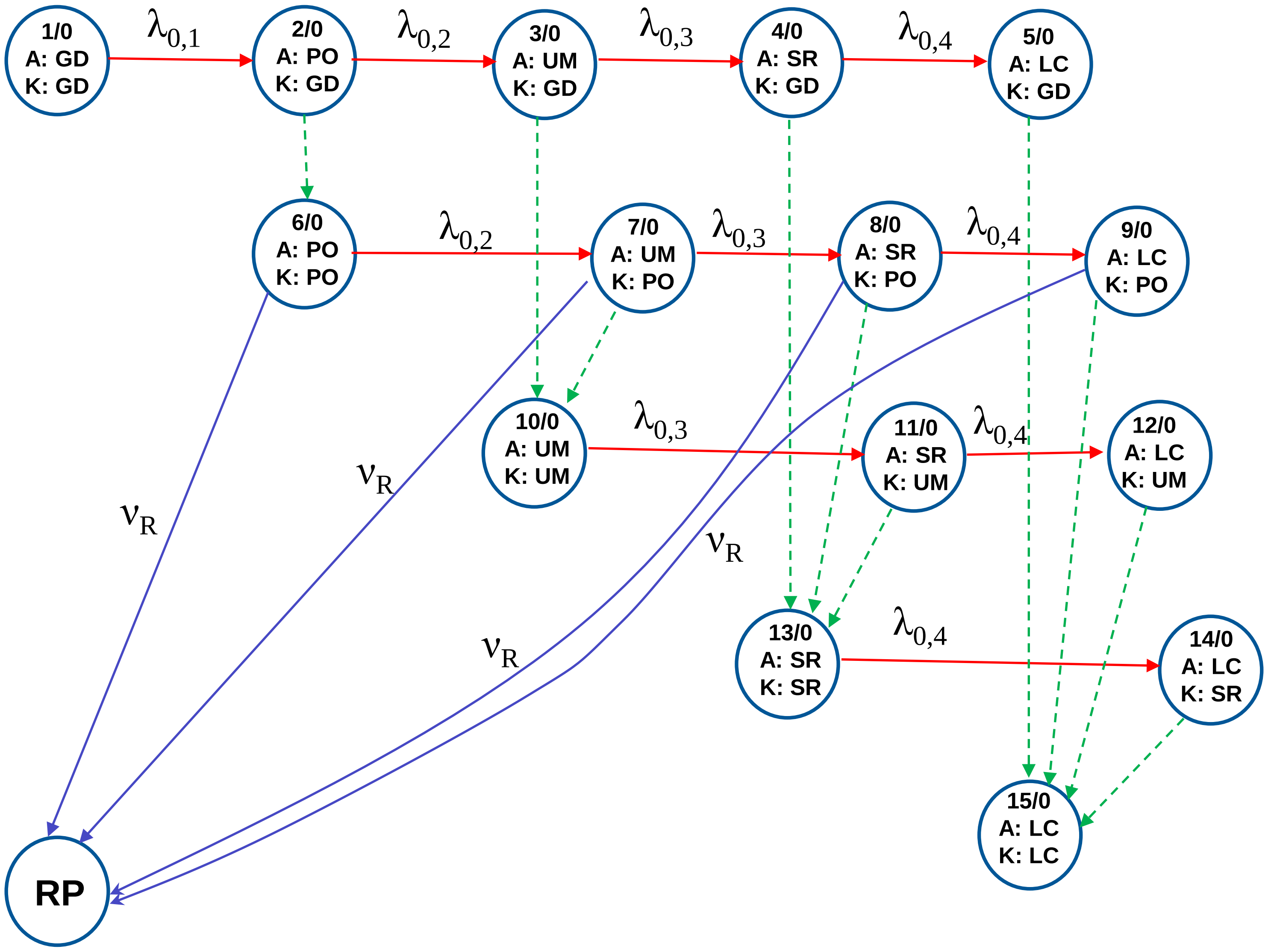
Degradation / Inspection

Track Geometry Markov Model



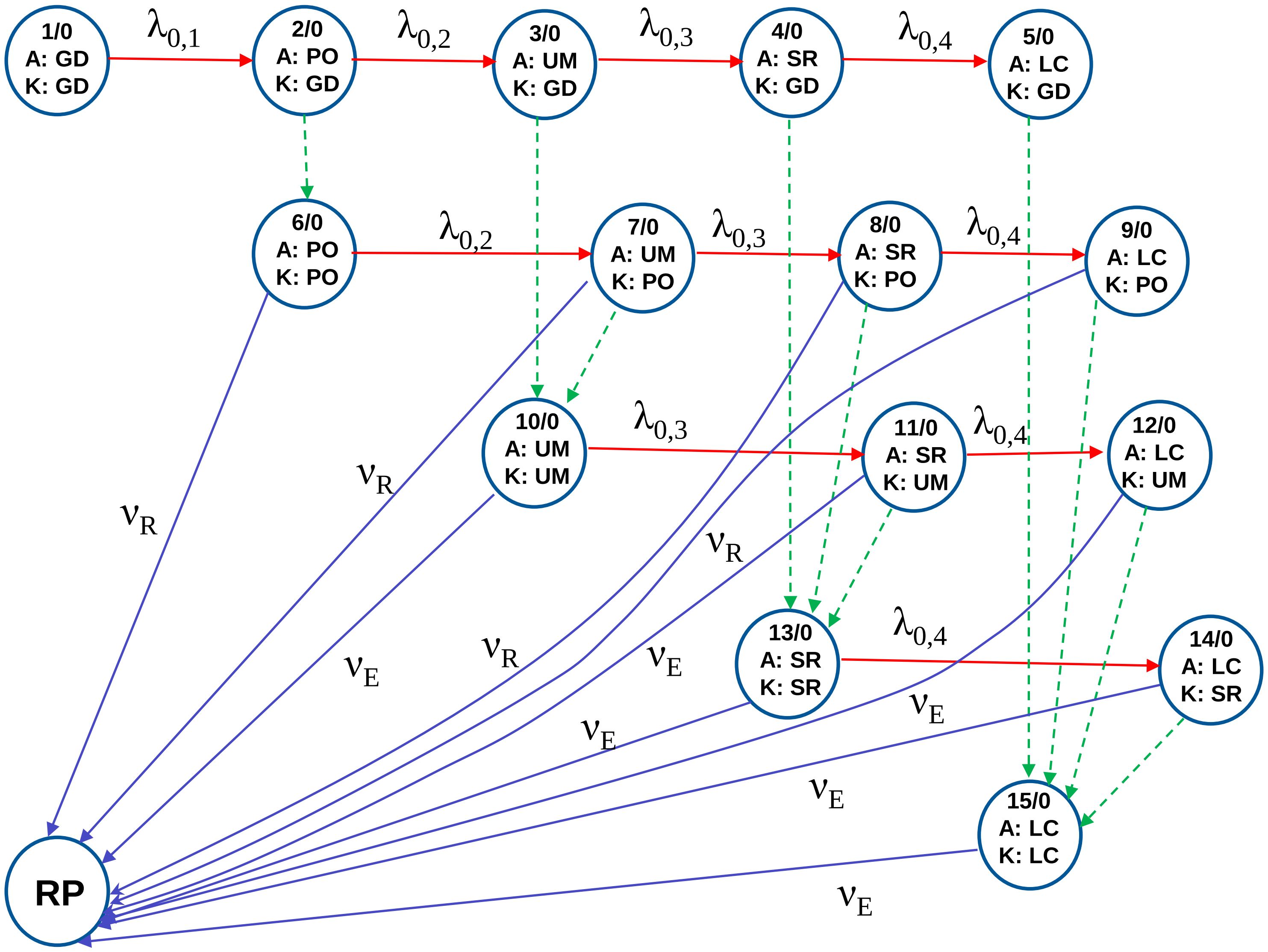
Degradation / Inspection

Track Geometry Markov Model



Routine Repair

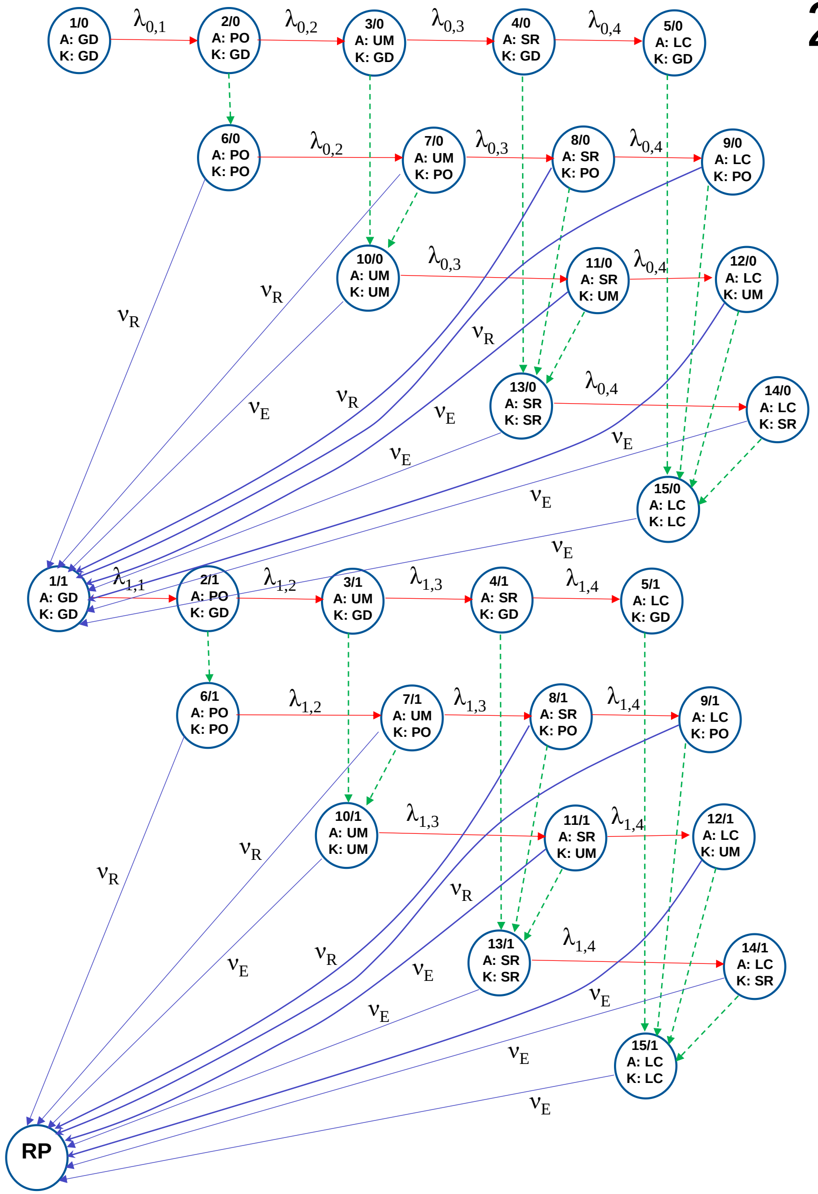
Track Geometry Markov Model



Emergency Repair

Track Geometry Markov Model

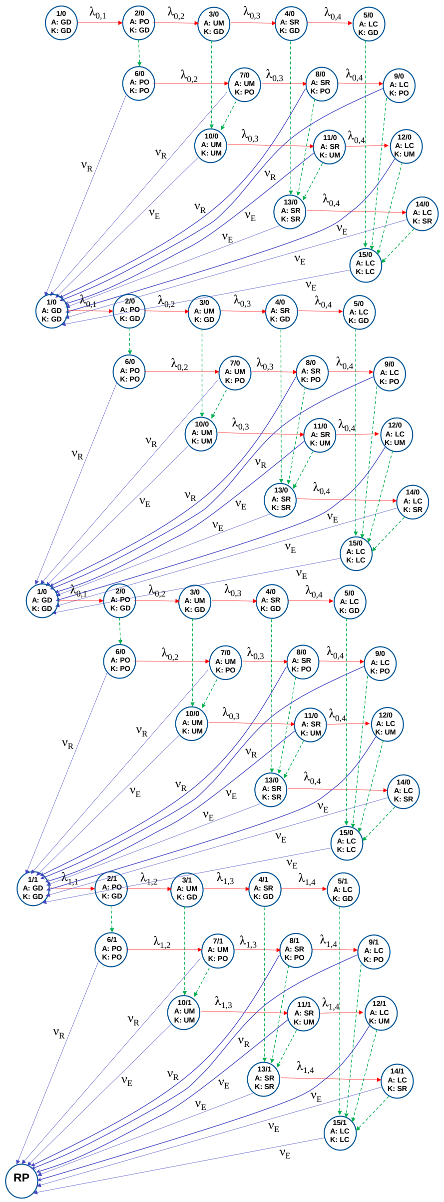
2 tamps



If it is assumed that after 7 tamps the degradation rates do not change. Then the model size will be:

- 105 nodes
- 105 simultaneous linear, first-order differential equations

4 tamps



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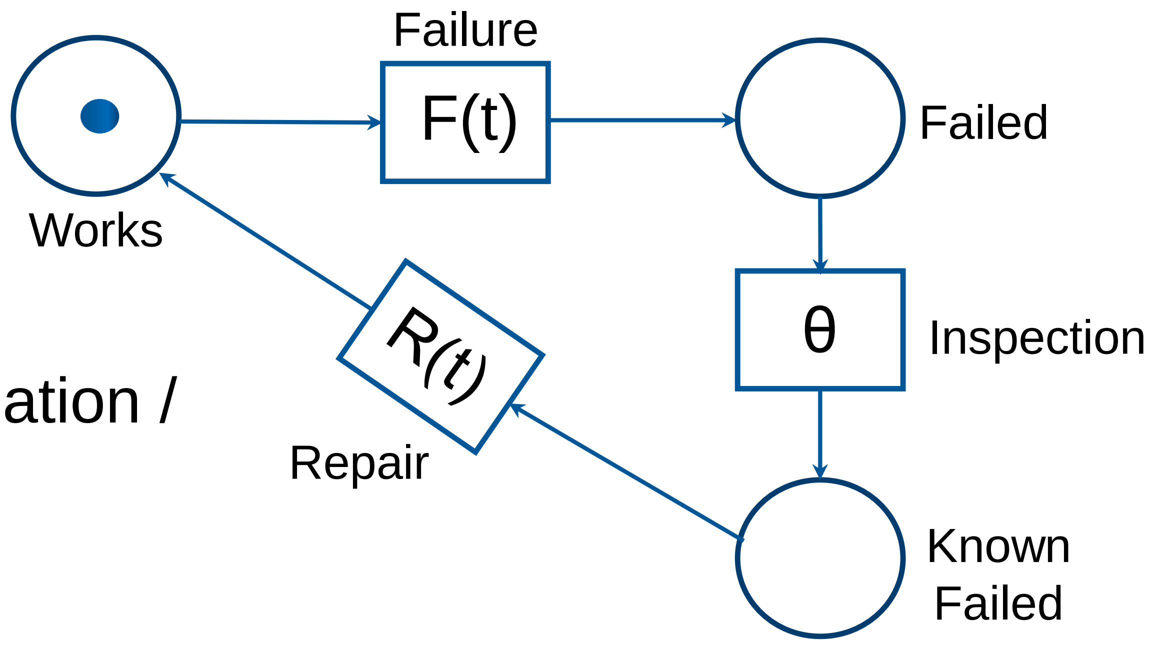
Petri Net Model

(1962)

Petri Net Models



Characteristics

- Any distribution of times for a transition
- Capable of modelling very complex degradation / maintenance strategies / dynamics / dependencies
- Concise structure

Solution

- Monte Carlo simulation

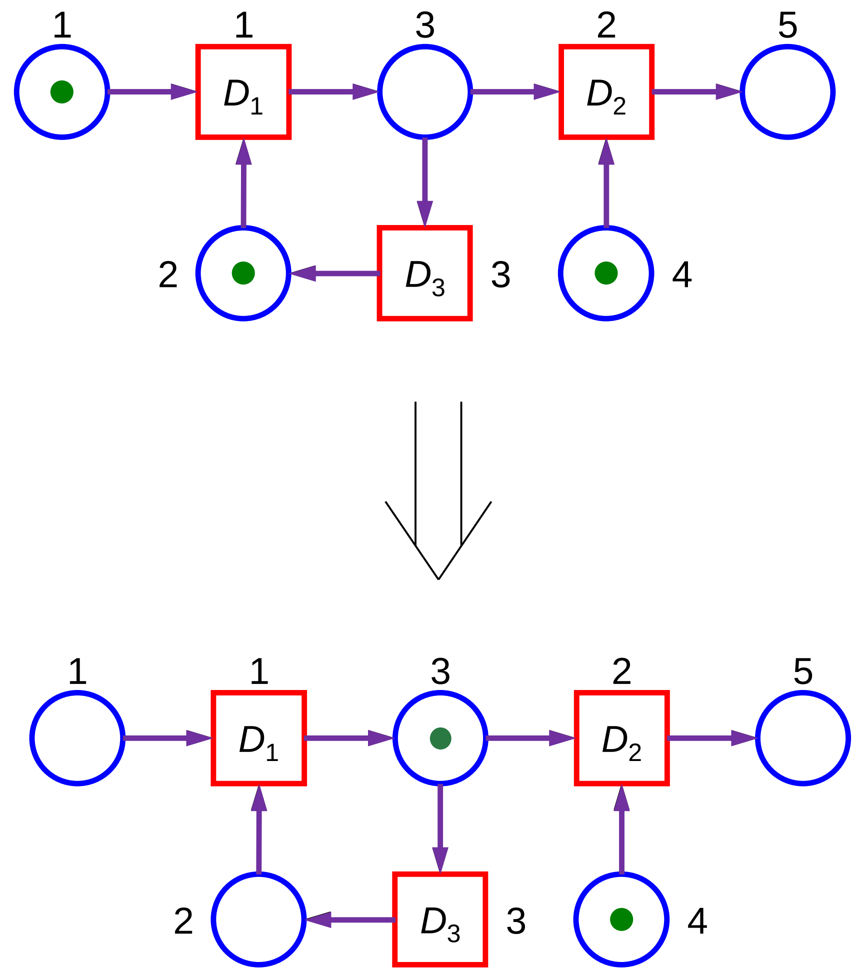
Outputs

- distributions of the durations in any state
- distributions of the number of occurrences of entering any state

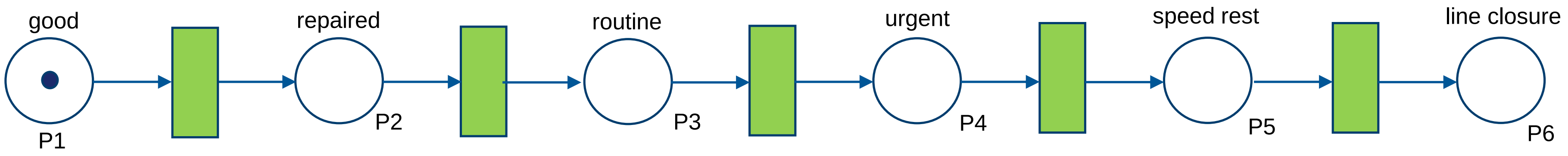
Petri Net Modelling - transitions

- If all input places of a transition are marked by at least one token then this transition is called **enabled**.

- After a delay $D_1 \geq 0$ the transition **fires**.
  - The firing removes one token from each of its input places and adds one token to each of its output places.

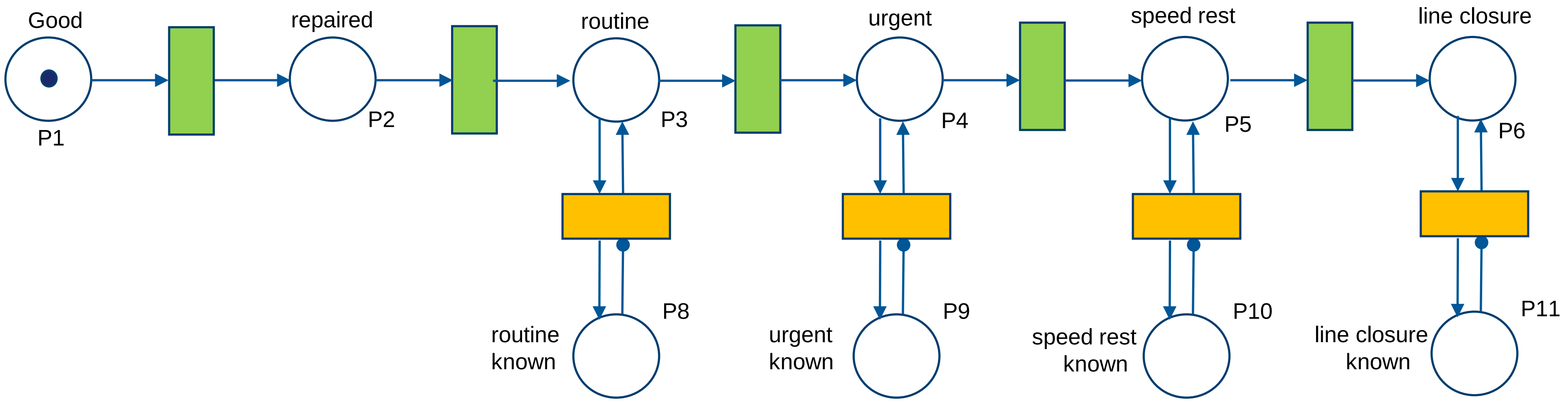


Track Geometry Petri Net Model



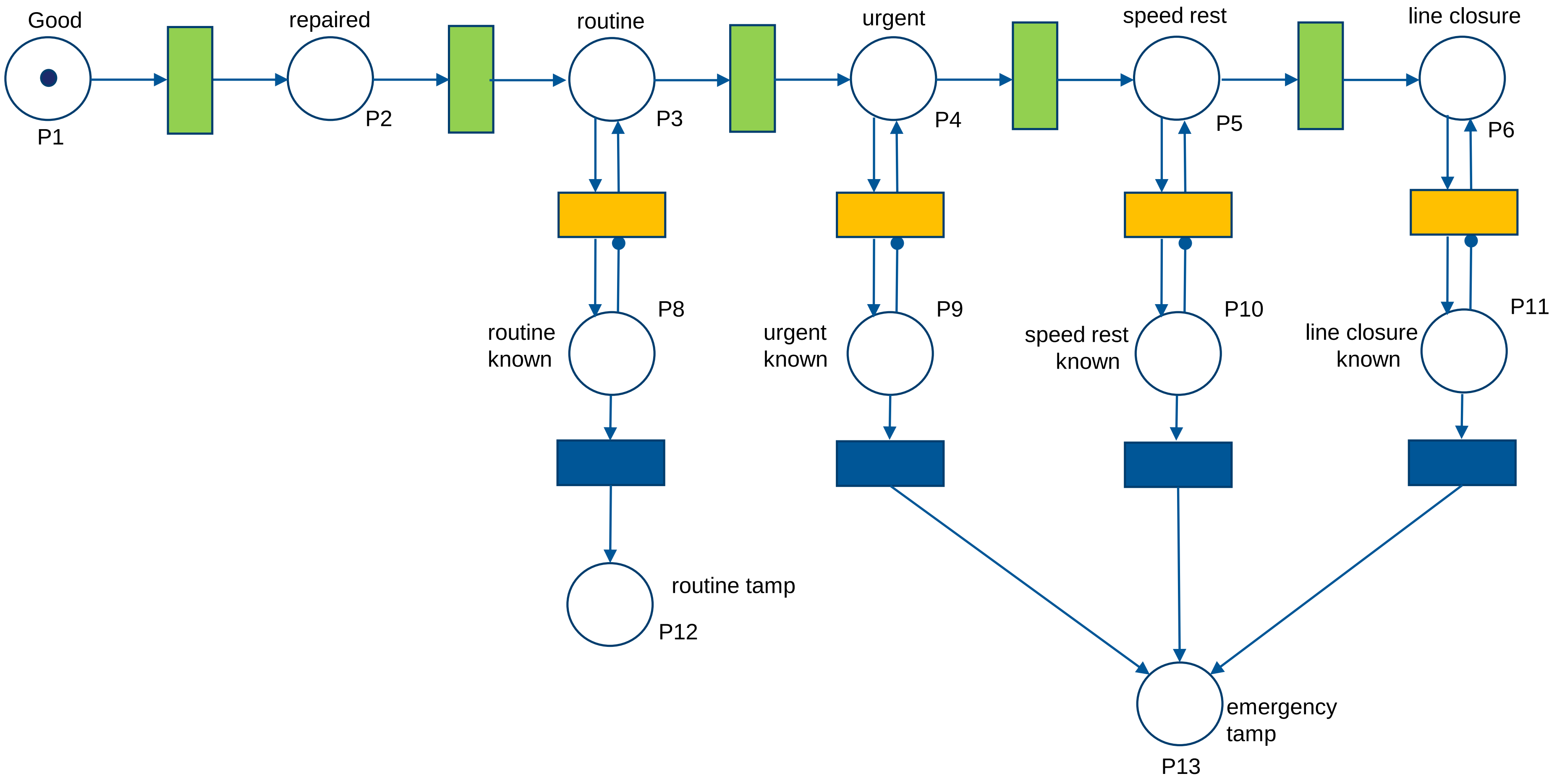
Degradation

Track Geometry Petri Net Model



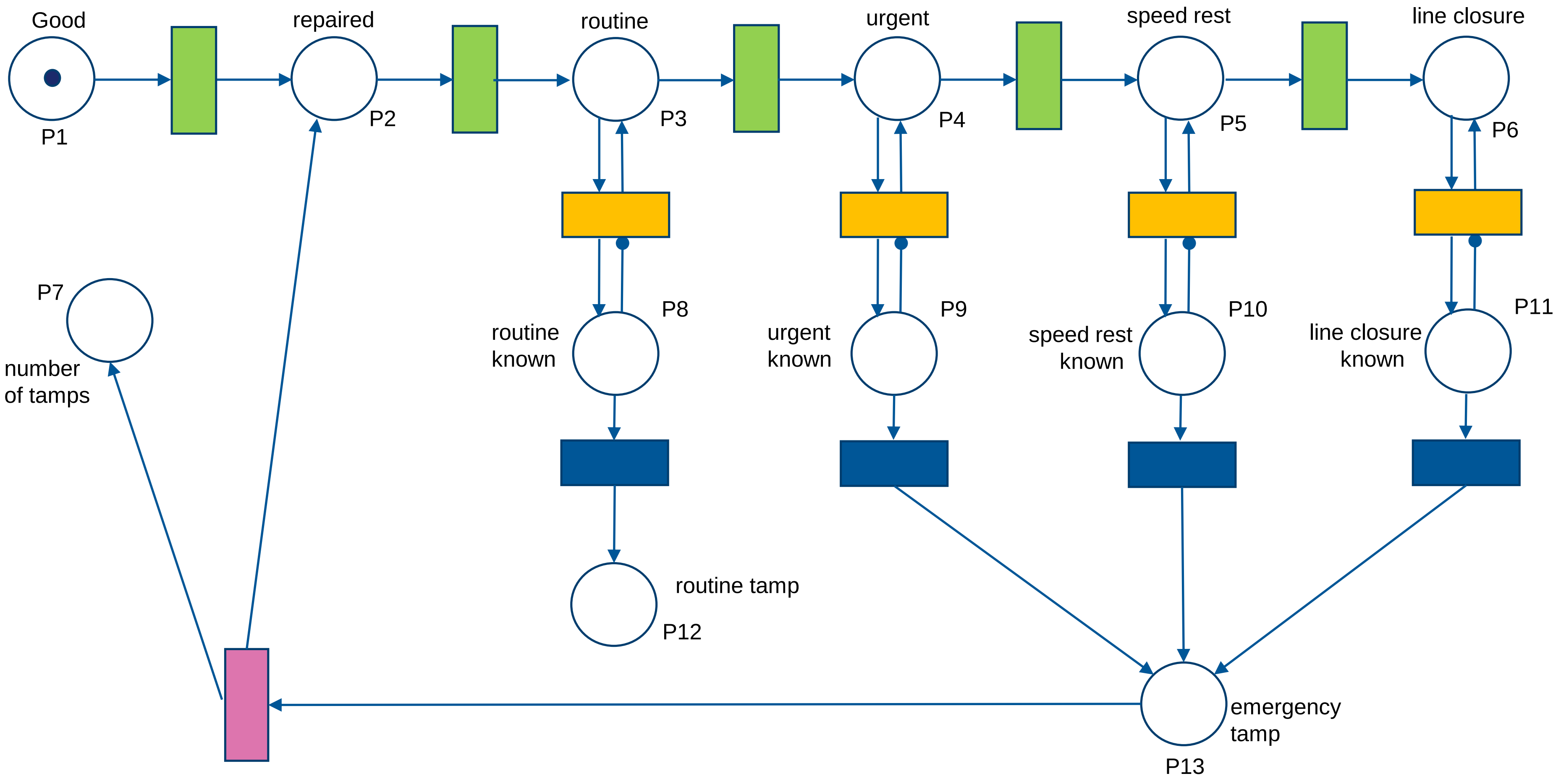
Inspection

Track Geometry Petri Net Model



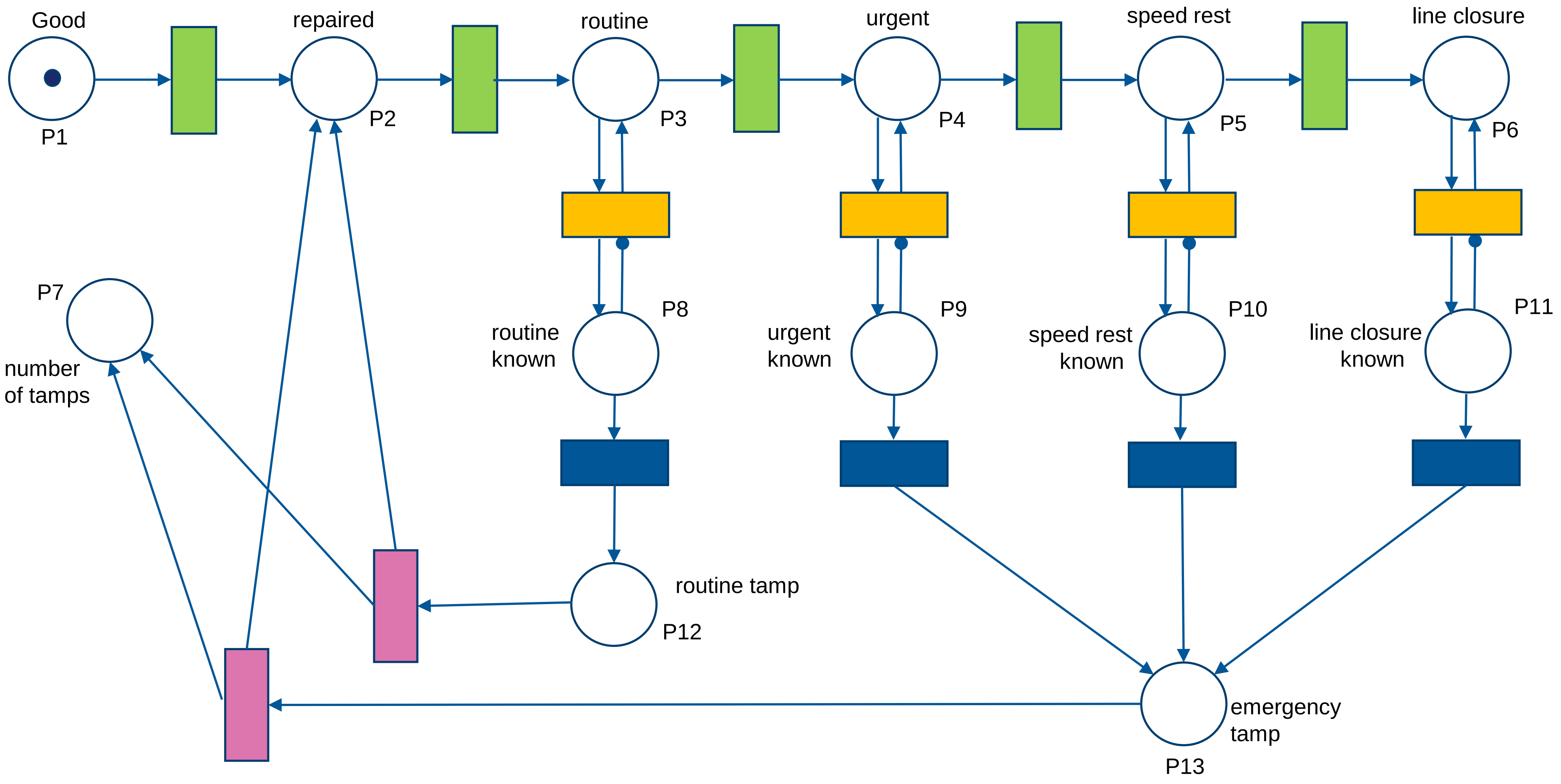
Repair Options

Track Geometry Petri Net Model



Emergency Repair

Track Geometry Petri Net Model



Number of states - 13

Number of transitions - 15

Routine Repair

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Model results – Asset Condition Performance

Condition	Condition Known?	Min Value	Average Value	Max Value	Comment
Good		62.66%	65.2%	67.31%	
Repaired to		30.27%	30.42%	30.59%	
Routine maintenance		2.58%	3.11%	5.72%	
Urgent		1.12%	1.16%	1.18%	
Speed Restriction needed	Known	0.0%	0.005 %	0.018 %	Service disruption
	Unknown	0.0%	0.043 %	0.056 %	Potential safety issue
Line Closure needed	Known	0.0%	0.005 %	0.018 %	Service disruption
	Unknown	0.0%	0.057 %	0.07 %	Potential safety issue

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Model results – Maintenance Volumes

Event	Number		
	Min	Average	Max
Track Inspections	391	391	391
Routine Intervention (tamp)	0.0	3.7	12.5
Emergency Intervention (tamp)	0.0	2.58	3.11
Speed Restriction	0.0	0.2	2.3
Line Closure	0.0	0.028	1.57

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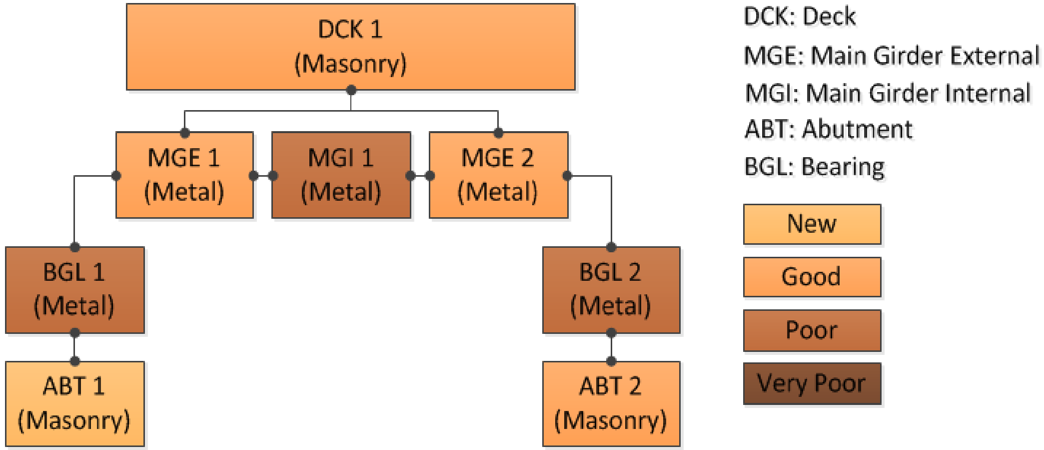
Bridges



Degradation (unmeasured)

- Structure with several components
  - Deck
  - Main Internal girder
  - Main external girder
  - Abutment
  - Bearings
- Degradation Modes
  - Depends on component
  - Depends on material
  - Components can have several failure modes

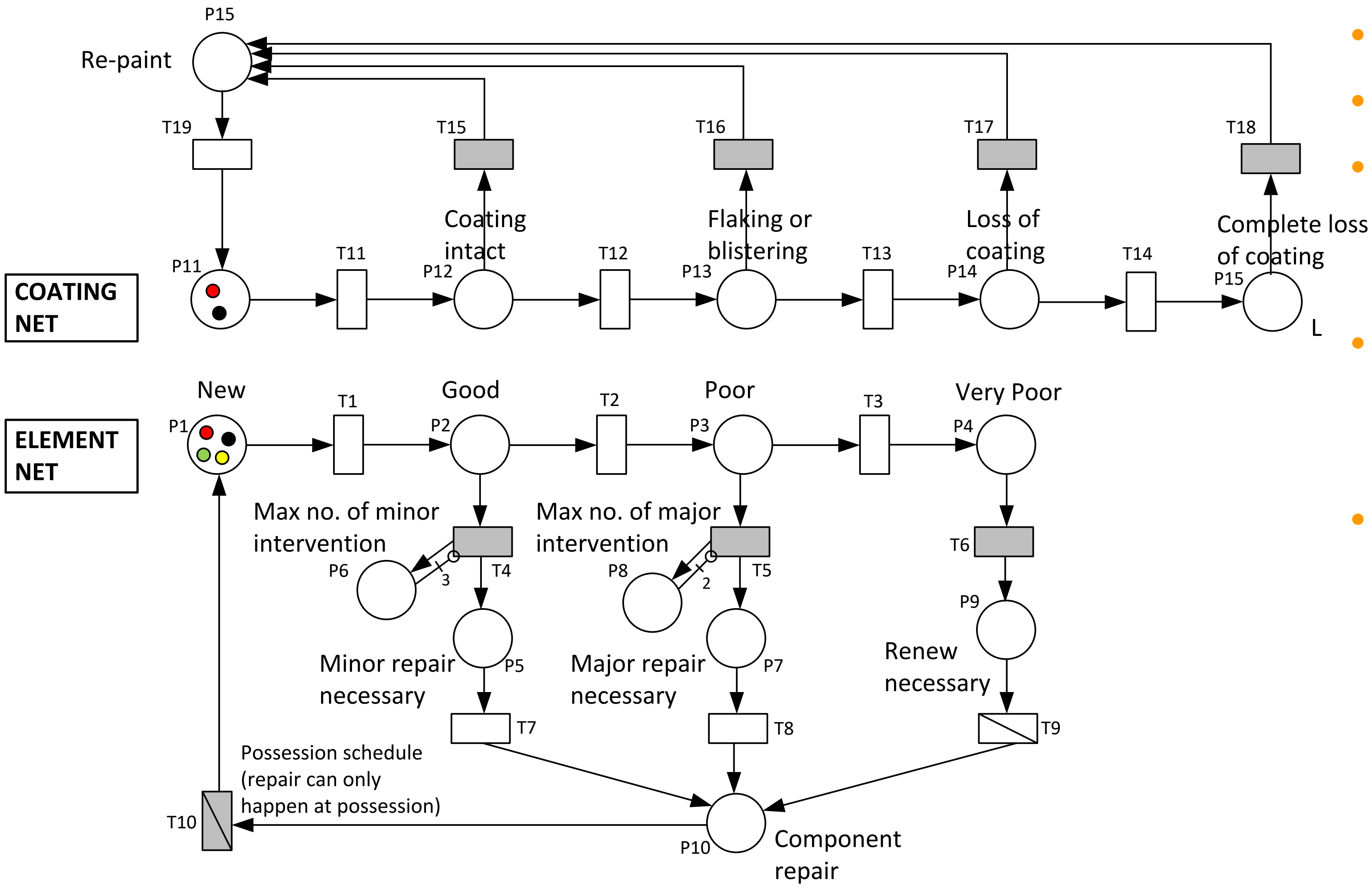
Inspection

Manual inspection (observations)

Intervention

Depends on component and degradation mode

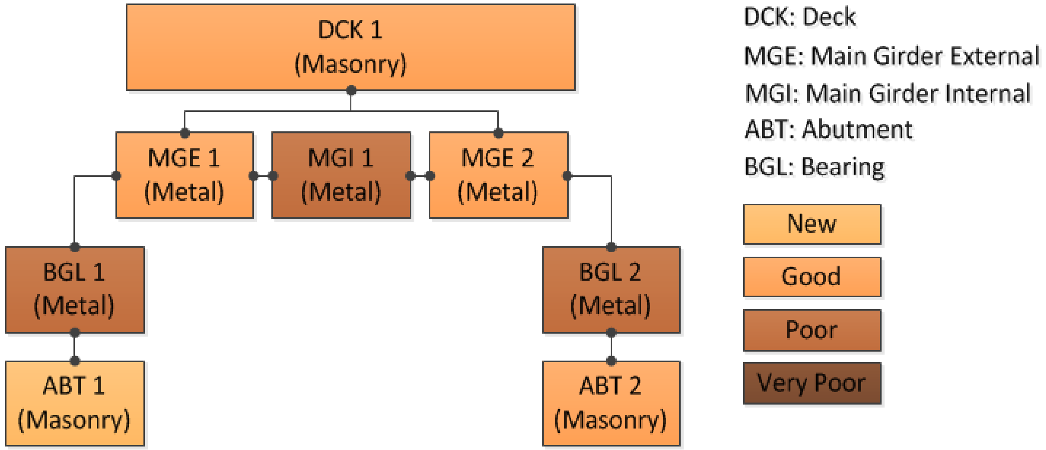
Bridge Petri Net Model



Features

- Coloured Petri Net
- Concise model structure
- Degradation of the metal related to the condition of its protective paintwork.
- There is a limit to the number of times each type of maintenance can be completed.
- Opportunistic maintenance where repair of a component requires other to be replaced at the same time.

Bridges



Markov modelling of the bridge

- Not a directly comparable model to the Petri Net
- 8 components with 4 levels of degradation: 65,536 states
- 8 components, taking account of the protective coating: 4,194,304 states

Observation – Petri Net Models

Petri Nets have the ability to represent the diverse range of processes that are experienced in asset management within a concise model structure.

- Its structure follows the engineering processes
- Models realistic degradation and maintenance time distribution
- Concise structure
- Dependencies (opportunistic maintenance / replace connected components) can be represented
- Degradation dependent upon maintenance history can be represented
- Maintenance effectiveness can be limited to a specified number of interventions

Additional Implications of choosing the Markov method

Characteristics - Memoryless property

Assumes the future transition only depends on its current state and not the history of previous transitions

Consider Track Geometry:

- Currently in the acceptable state for vertical geometry (no previous tamps)

OR

- Currently in the acceptable state for vertical geometry (6 previous tamps)

- Transition rate conditional on tamping history – many states on the model max no of tamps defined

Markov Analysis – implications for asset management

- Characteristics - Constant rates of transition (exponential distribution for residence times)

Assumes that components are repaired with a constant rate (random process)
Repair is not a random process and it can be argued this never has a constant rate!

Markov Analysis – implications for asset management

- Characteristics - Constant rates of transition (exponential distribution for residence times)

Assumes that components fail with a constant rate

Considering preventive maintenance – replacement prior to failure after time T_1

- costs £X
- replaces an item with failure rate λ with a new one which fails with rate λ.

This form of model will never make replacement prior to failure a sensible option

Markov Analysis – implications for asset management

- Characteristics - Exponential distribution for residence times (constant rates of transition)

Assumes that components fail with a constant rate
Considering preventive maintenance – replacement prior to failure after time T_1 • costs £X • replaces an item with failure rate λ with a new one which fails with rate λ. This form of model will never make replacement prior to failure a sensible option
Infrastructure intensive industries such as railways commonly feature aging assets which experience wear-out (increasing failure rate)

Observation – Markov Models

Use of Markov models for asset management needs to be considered carefully.

Some of the assumptions implicit in the method may not easily fit the engineering processes being modelled.

Model sizes can become very large for moderately sized problems.

System modelling

System / Route / Network Models

Better quality decisions can be supported by producing ‘route’ level models.

- Avoids artificial budgets allocated to different asset groups
- Enables resources to be allocated to the correct part of the system at the correct time it is needed.
- Enables concurrent maintenance on many assets during a track possession

Asset Model constructed from component models

electrification / signalling / communications / bridges

Route Model constructed from asset models

rail / sleepers / ballast / S&C / drainage

Can sub-models be linked to create a ‘system’ level model?

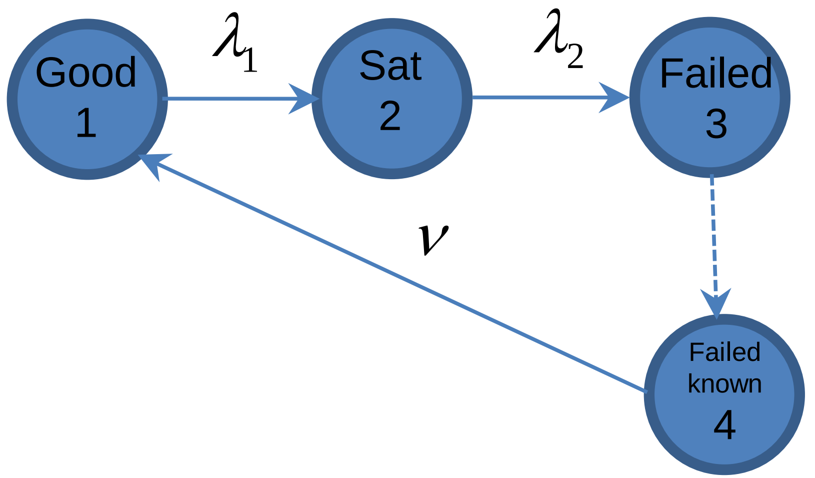
Model Construction Process – two component system

Two Component system

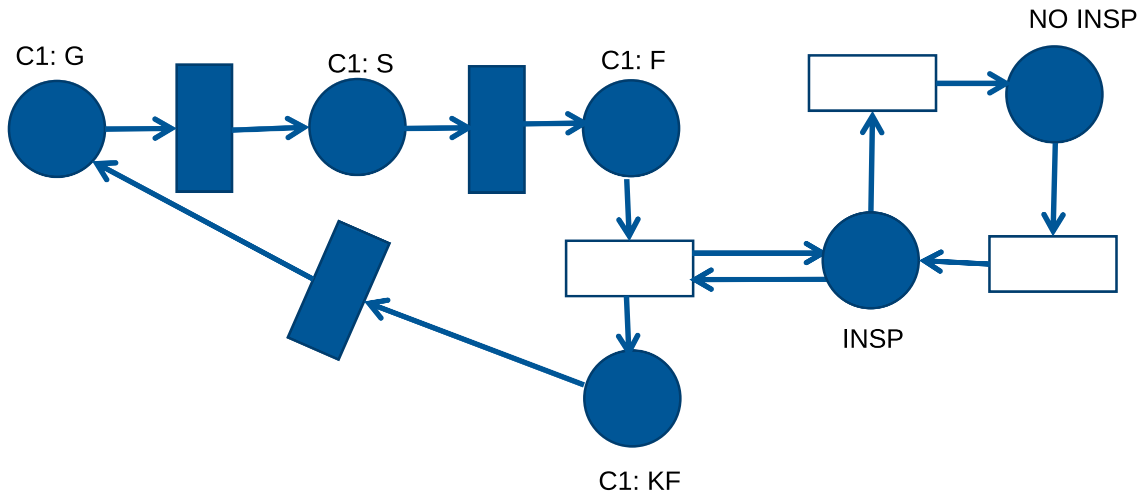
- Each component has 3 states
  - New/good
  - Satisfactory
  - Failed
- Failures are unrevealed and discovered on inspection.
- Common inspection process for both components.

Component Models

Markov Model

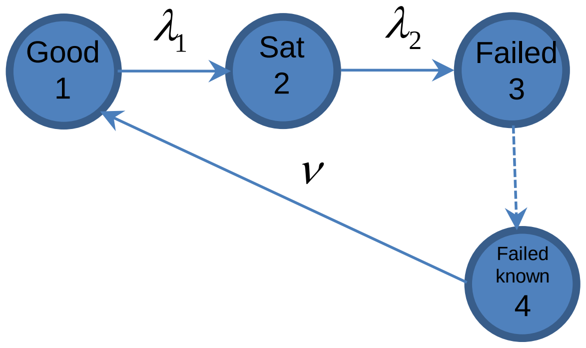


Petri Net Model

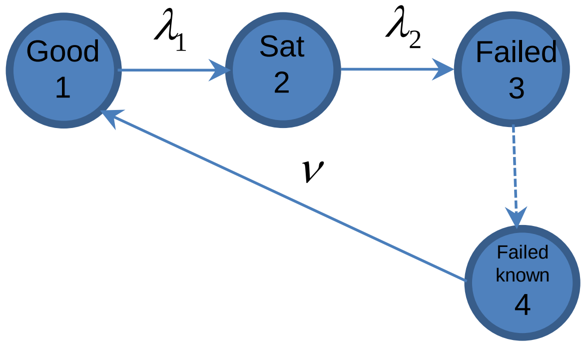


Markov Approach – System Model

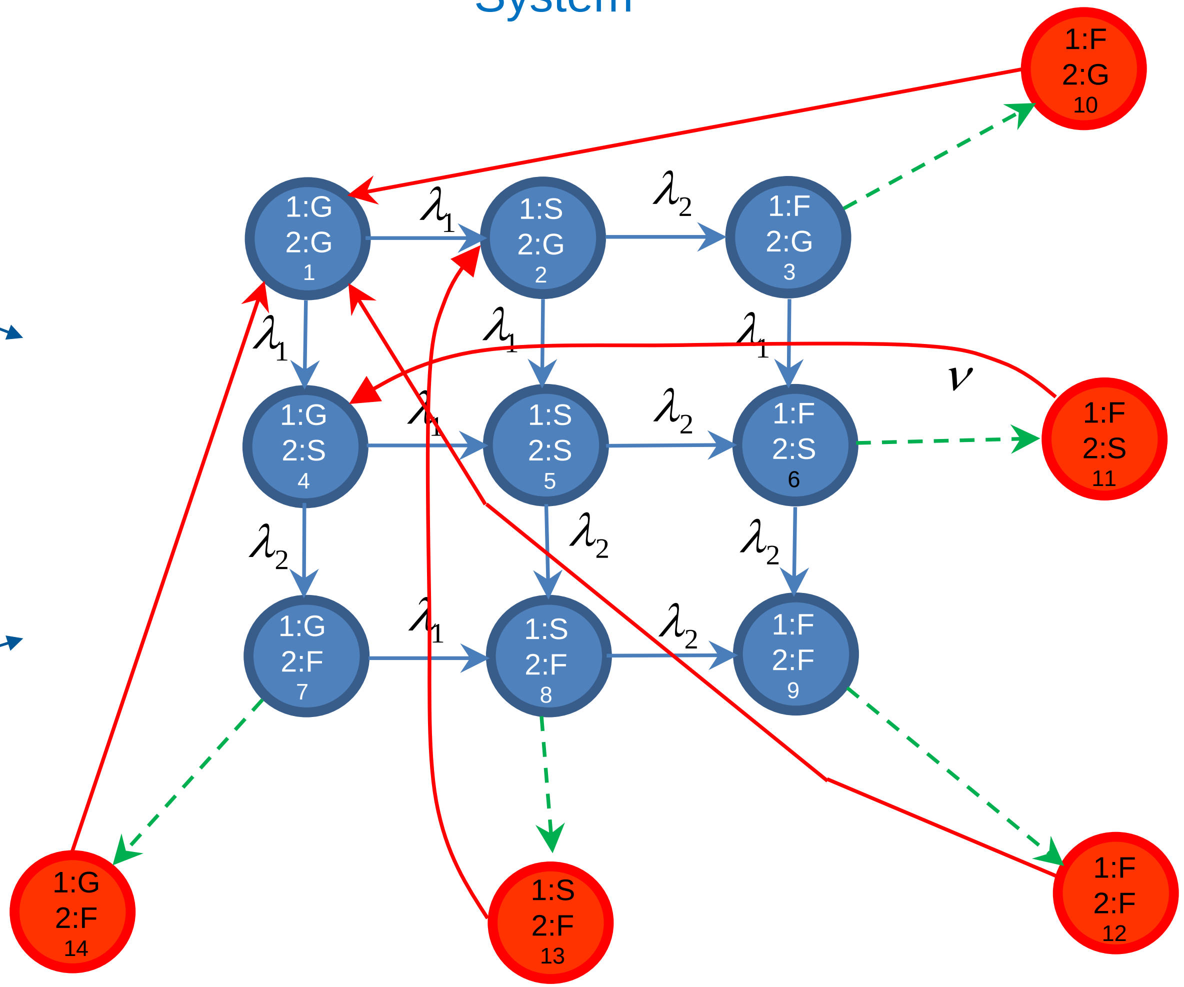
Component 1



Component 2



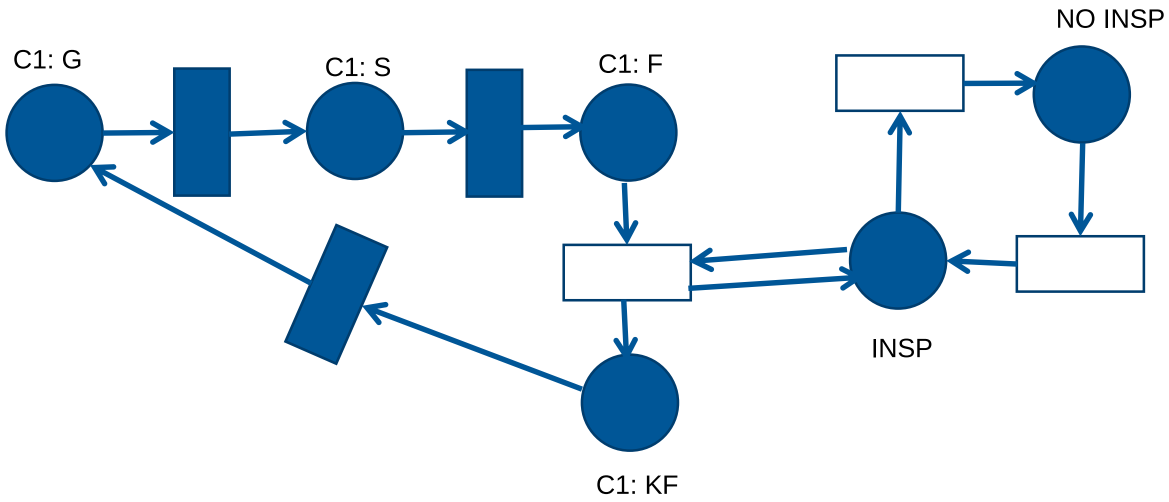
System



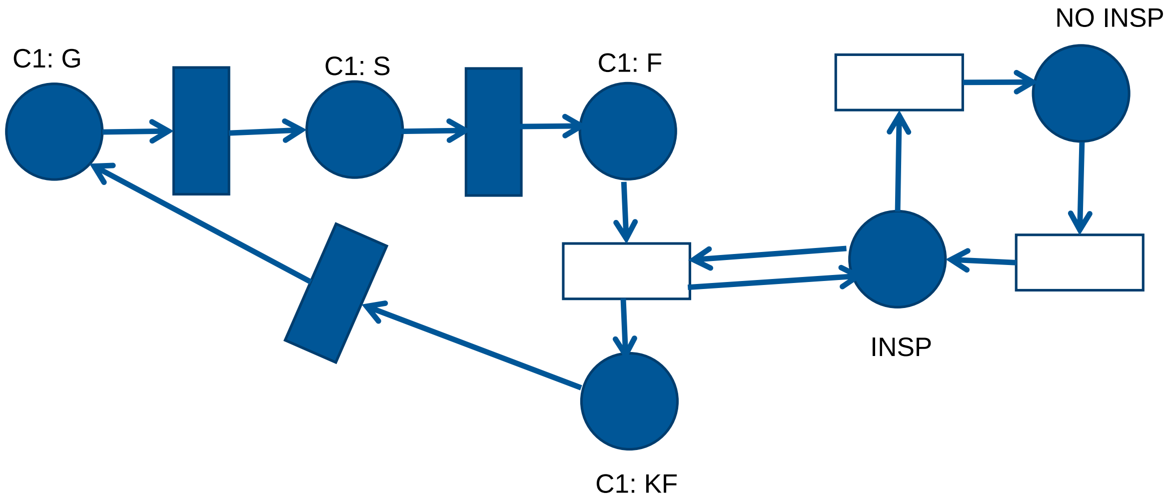
Component Models cannot be combined

Petri Net Approach – System Model

Component 1



Component 2



Petri Net Approach – System Model

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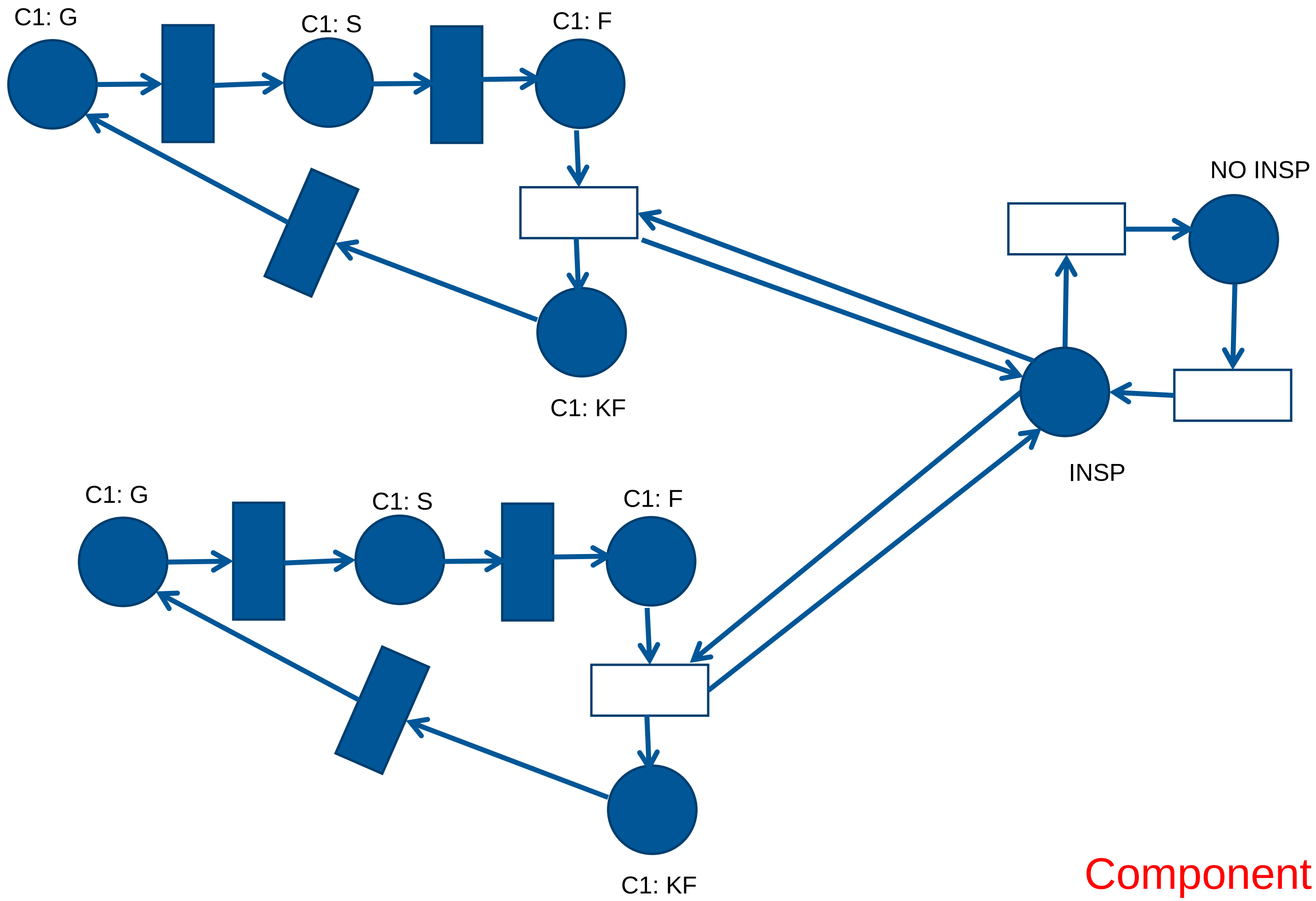
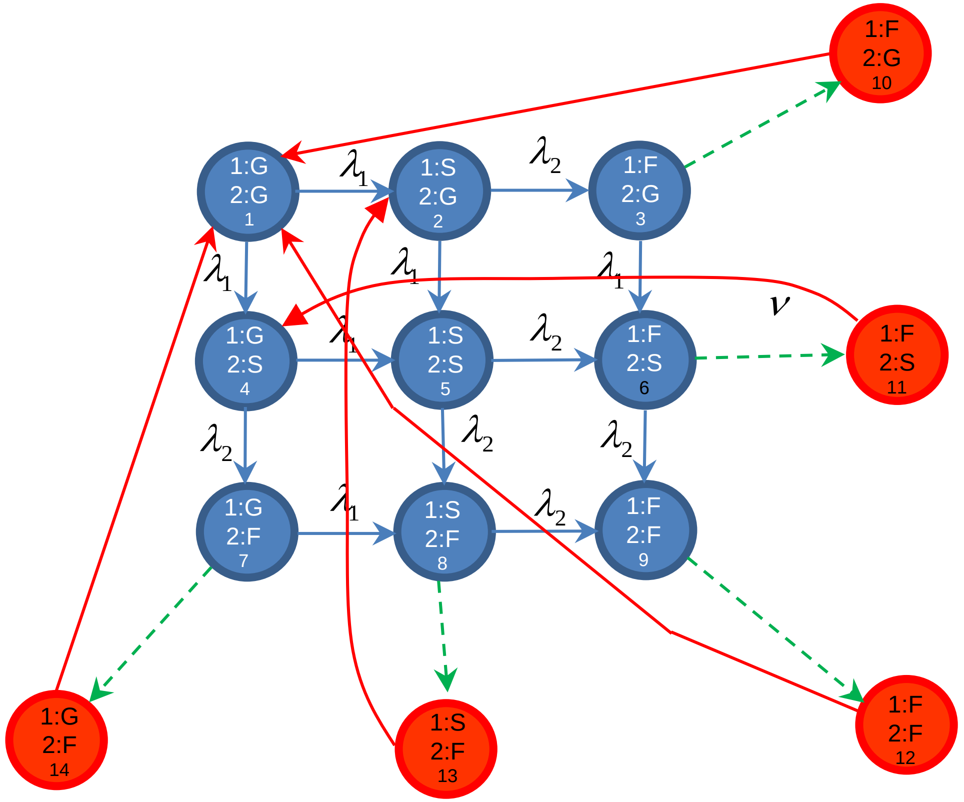
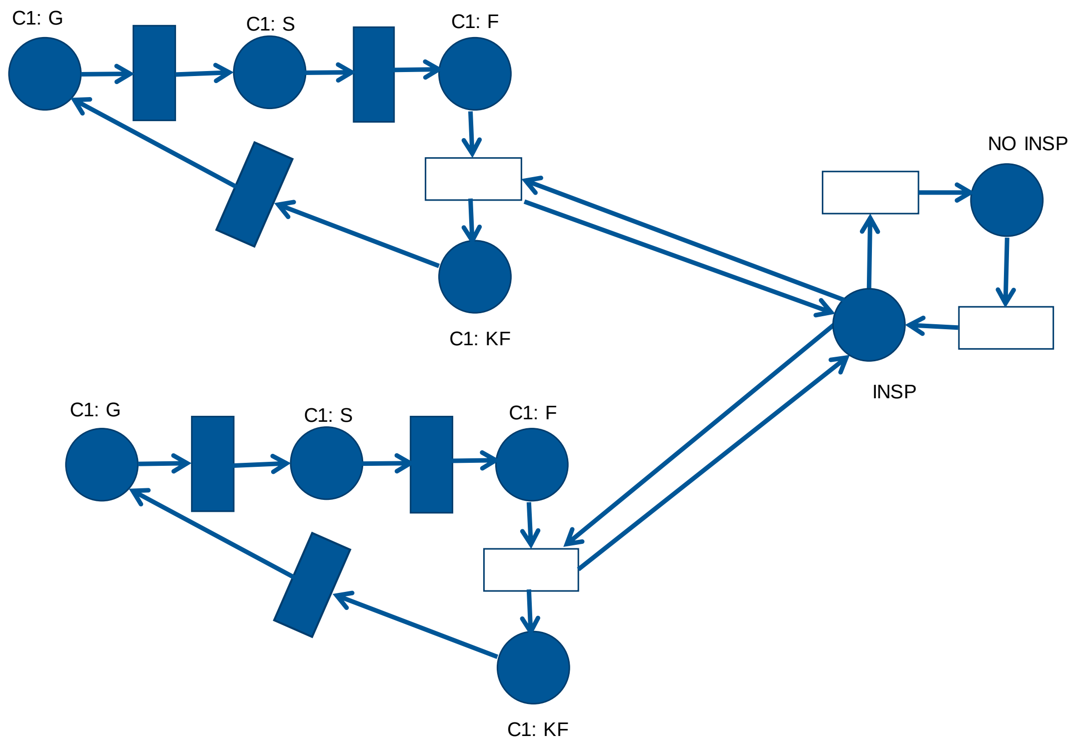


Component Models are additive

Markov v Petri Net





Components	states
1	4
2	14
3	42

Components	Places
1	6
2	10
3	14

Observation

For system / route model development:

Petri Nets can be constructed by linking sub-models of the assets or components

Markov models require a completely new model to be developed which grows exponentially with the number of components

Main Conclusions

- *Petri nets and Markov approaches can both be used to predict the performance of asset management strategies.*

- *Markov models*
  - *are restricted through having constant rates of transition between the model states.*
  - *The model size can become very large for relatively moderate problems.*

- *Petri Nets*
  - *provide a very effective option for developing concise models which require few assumptions to be made on the underlying engineering processes.*
  - *the diverse range of interventions can be accommodated in such models.*
  - *efficient scale-up to route models is possible through linking the asset models.*

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Any Questions?