29th Annual INCOSE international symposium

Orlando, FL, USA
July 20 - 25, 2019

London Underground Deep Tube Upgrade Programme (DTUP)

System Function Definition Model Case Study

Paper #24

Paper written in collaboration between:

wsp

Transport for London

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Core Presentation Themes

This presentation will cover the following core elements:

- A bit about London Underground and the Deep Tube Upgrade Programme (DTUP)
- How we developed the functional model for DTUP, what we did, and why we did it the way we did.
- Elaborate some aspects of the paper.
- Accessibility of systems engineering techniques to non-SE practitioners and tailoring to their needs.

Introduction

About the London Underground Network

London Underground, better known as the Tube, is the world's oldest underground railway network, and one of the largest.

- First line opened in 1863
- Comprises of 11 lines
- Covers a total of 402km
- Serves 270 stations
- Handles up to 5 million passenger journeys per day.

With more people than ever using the Tube, ongoing improvements are essential to manage ageing assets and ensure the tube continues to operate effectively.

https://tfl.gov.uk/corporate/about-tfl/what-we-do/london-underground

About the Deep Tube Upgrade Programme (DTUP)

The Deep Tube Upgrade Programme (DTUP) is an upgrade of four "Deep Tube" underground lines:

- **Piccadilly Line (Opened 1906)**
- **Bakerloo Line (Opened 1906)**
- **Central Line (Opened 1900)**
- **Waterloo and City Line (Opened 1898)**

https://en.wikipedia.org/wiki/History_of_the_London_Underground#/media/File:Why_London_Underground_is_nicknamed_The_Tube.jpg
Image released for use in public domain.

https://tfl.gov.uk/corporate/about-tfl/culture-and-heritage/londons-transport-a-history/london-underground/a-brief-history-of-the-underground

About the Deep Tube Upgrade Programme (DTUP)

The Deep Tube Upgrade Programme (DTUP) has the following key objectives:

- Maximising capacity: delivering a **36 per cent increase** across the four Deep Tube lines
- Reducing journey times: through faster and higher frequency train services (**up to 33 trains per hour (tph)** on the Central and Piccadilly lines)
- Renewing life-expired assets more efficiently through a multi-line approach
- Improving safety and reliability: **a step-change in performance** through the introduction of modern train and signalling technologies
- Enhancing the customer experience: through the introduction of a consistent brand of new **air-cooled, fully accessible trains**
- Driving down whole-life costs through greater **standardisation in system specification, procurement, operations and maintenance**

http://content.tfl.gov.uk/pic-20180516-item08-deep-tube-update.pdf

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The DTUP Functional Model

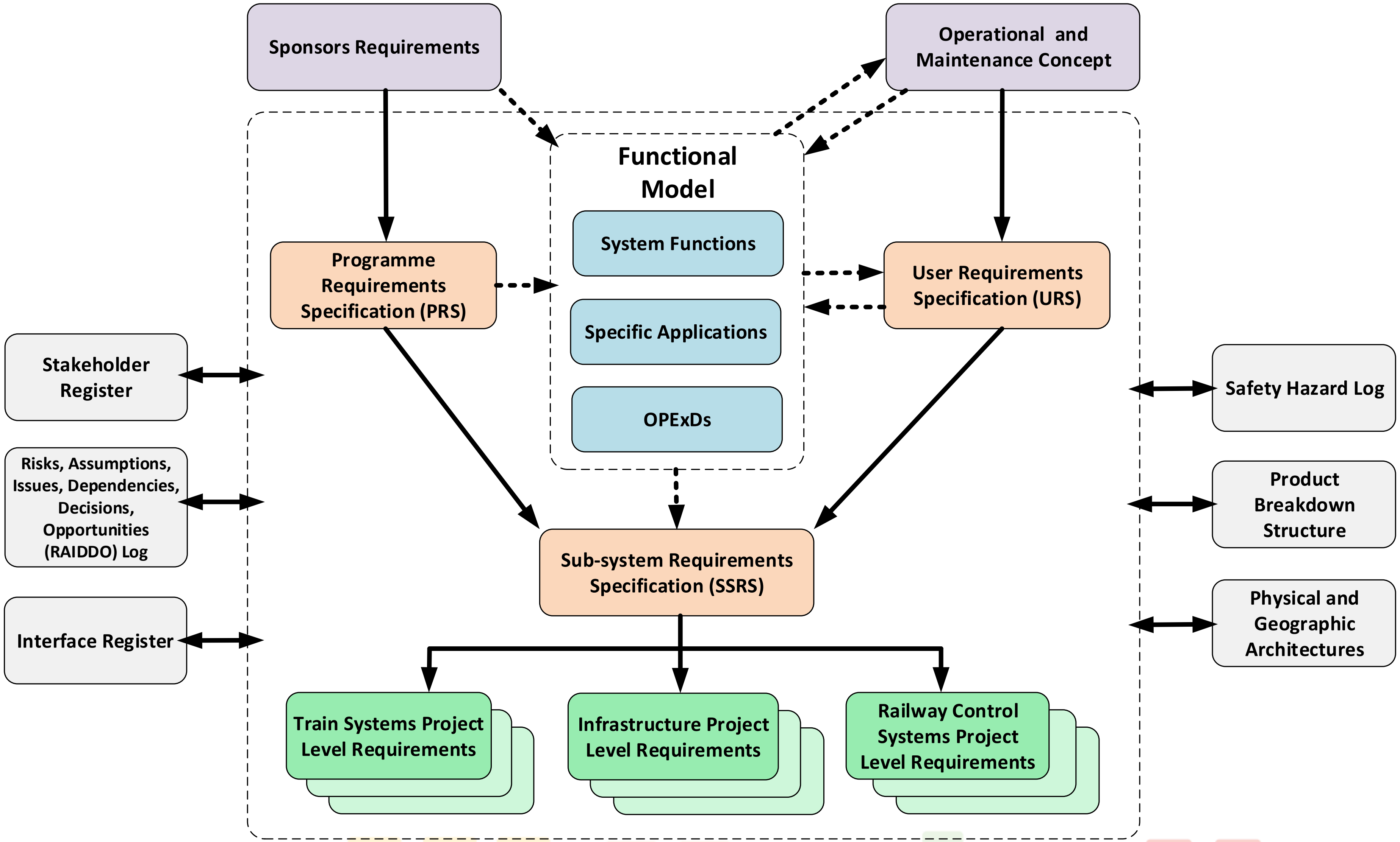
Why was a Function Model Needed?

- With an introduction of new technologies and significant service uplifts, this meant that the way the affected lines would be operated would be significantly different from today.

- To ensure completeness of the Operational and Maintenance Concepts and User Requirements, which informed the requirements and system design.

- A desire to ensure that the system was future proofed, meant that potential future operating modes needed to be considered.

DTUP Requirements Structure



High Level Methodology for Developing the Functional Model on DTUP

1. Sponsor Requirements and Operational / Maintenance Concept used to **identify core functions**.
2. **Functional Descriptions** written for the identified functions.
3. **Specific Applications** identified for each function.
4. **Operational Process Execution Diagrams (OPExDs)** developed for each of the Specific Applications.
5. Operational Process Execution Diagrams **reviewed by Specialist Engineers** (e.g. Safety or RAM Engineers).
6. **Additional Functions** included if required, or in some cases removed or consolidated.
7. Development of **functional system level requirements** from the OPExDs, and use of **Satisfaction Matrices** to ensure full coverage.

DTUP System Functions

Normal Service
- Prepare Train for Service
- Move Train from Location to Location
- Open Customer Doors / PTI Equipment at a Platform
- Close Customer Doors / PTI Equipment at a Platform
- Empty a Train

Operator Initiated Service Updates
- Execute Platform Skip
- Provide Information to Customers
- Transition between Signalling Regions

Operational System Management
- Raise System Notifications
- View CCTV
- Create Service Plan
- Control Traction Current
- Respond to PEA
- Apply or Remove Zone of Protection
- Reset PEA
- Operate Traction Current Switches
- Transfer Control of Railway from One Location to Another
- Edit System Parameters

Service Affecting Issues
- Evacuate Customers from a Train
- Respond to a Train Derailment or Collision
- Operate Emergency Stop
- Apply Code Red
- Remove Code Red
- Suspend Service
- Resume Service
- Detect Smoke
- Apply Code Amber
- Remove Code Amber
- Couple Passenger Trains
- Un-couple Passenger Trains

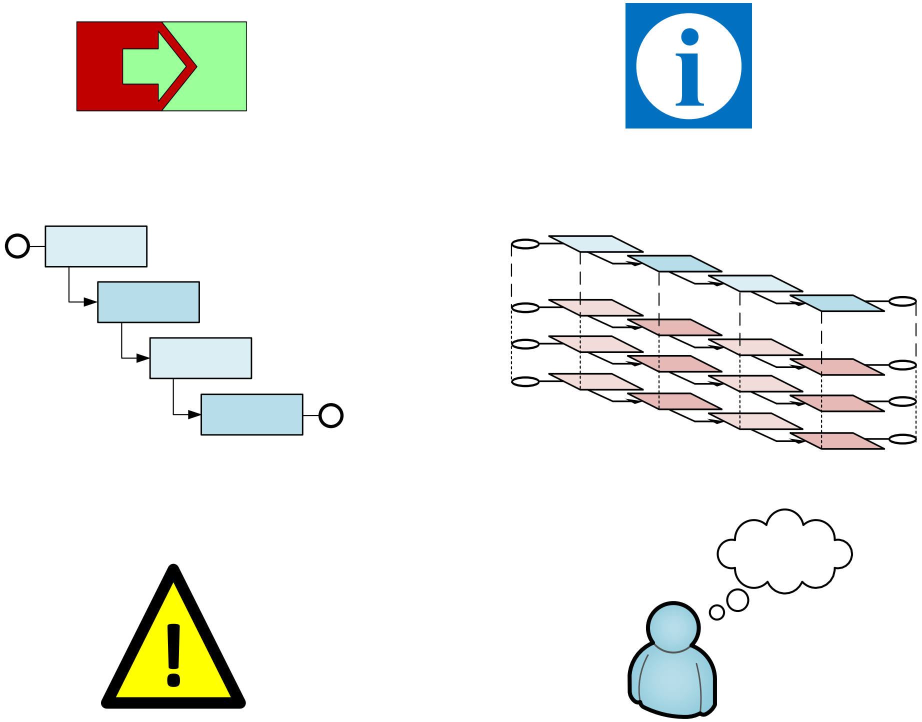
Avoiding Service Affecting Issues
- Detect Rough Ride
- Deploy De-icing Treatment to Conductor Rails
- Brush Sleet and Snow from Conductor Rails
- Manage Adhesion

Non-service Functions
- Schedule Asset Maintenance
- Set or Remove TSR
- Member of Staff Boards a Stabled Train
- Member of Staff Alights a Stabled Train
- Switch Train Power Supply
- Direct Staff Movement
- Control Tunnel Ventilation

Anatomy of a Functional Description

A functional description comprised of:

1. Transformation
2. Summary / Description
3. Process Steps
4. Specific Applications
5. Exceptions
6. Additional Considerations



Example Function – Open Customer Doors at a Platform

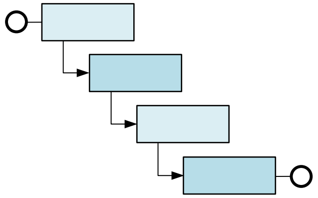
1. Transformation

Train doors go from a **closed state** to an **open state** at a passenger platform.

2. Summary

This function opens the customer doors such that they are aligned *with a useable and safe platform* interface at a station. Part of this function ensures that the relevant prerequisite conditions are met before the Train doors are opened, and that suitable notifications are raised to influence customer behaviour and to provide awareness.

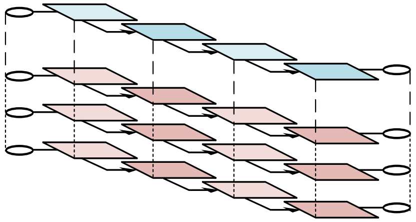
Example Function – Open Customer Doors at a Platform



3. Process Steps:

- Confirm that the Train has come to a stop within appropriate tolerance of the correct stopping position
- Identify which side(s) of the Train to open the customer doors
- Identify any Train doors/Platform Train Interface (PTI) equipment that should not be opened and inhibit the respective doors from opening
- Communicate which customer doors will and will not open
- Provide necessary instructions/handshaking/synchronisation between the Train and any ancillary PTI equipment
- Ensure that the relevant prerequisite conditions are met before customer doors are opened
- Provide audible and visual warnings of customer doors opening to customers inside the Train and on the platform
- Transition Train doors and required ancillary PTI equipment into an open/safe state

Example Function – Open Customer Doors at a Platform



4. Specific Applications (not an exhaustive list):

- Manually operated Train
- Legacy Attended Automatic Train (Central line)
- Attended Automatic Train at Migration State 6
- Manually open doors from the platform (Manual Operation)
- Manually open doors from the platform (Legacy Attended Automatic) (Central line)
- Manually open doors from the platform (Attended Automatic)
- Manually open doors from inside the Train (Manual Operation)
- Open doors of coupled Train (all variants, including legacy-DTUP and push / pull configurations)

etc…..

Example Function – Open Customer Doors at a Platform

5. Exceptions

- Confirmation that the Train has stopped in the correct location has not been provided.
- Train door fails to open.
- Prerequisite conditions (e.g. Stopping location, Correct Side Door Enable (CSDE), PTI Equipment, etc.) not achieved.

6. Additional Considerations

- This function needs to consider what happens when a train enters a platform from a non-normal direction.

Example Function – Open Customer Doors at a Platform

Transformation

Train doors go from a closed state to an open state at a platform.

Summary

This function opens the customer train doors such that they are aligned with a useable and safe platform interface at a station. Part of this function ensures that the relevant prerequisite conditions are met before the train doors are opened, and that suitable notifications are raised to influence customer behaviour and to provide awareness.

Process Steps

1. Confirm that the train has come to a stop within appropriate tolerance of the correct stopping position.
2. Identify which customer doors to open.
3. Identify any customer doors that should not be opened and inhibit the respective doors from opening.
4. Communicate which customer doors will and will not open.
5. Provide necessary instructions/handshaking/synchronisation between the train and any ancillary PTI equipment.
6. Ensure that the relevant prerequisite conditions are met before customer doors are opened.
7. Provide audible and visual warnings of customer doors opening to customers inside the train and on the platform.
8. Transition train doors and required ancillary PTI equipment into an open/safe state.

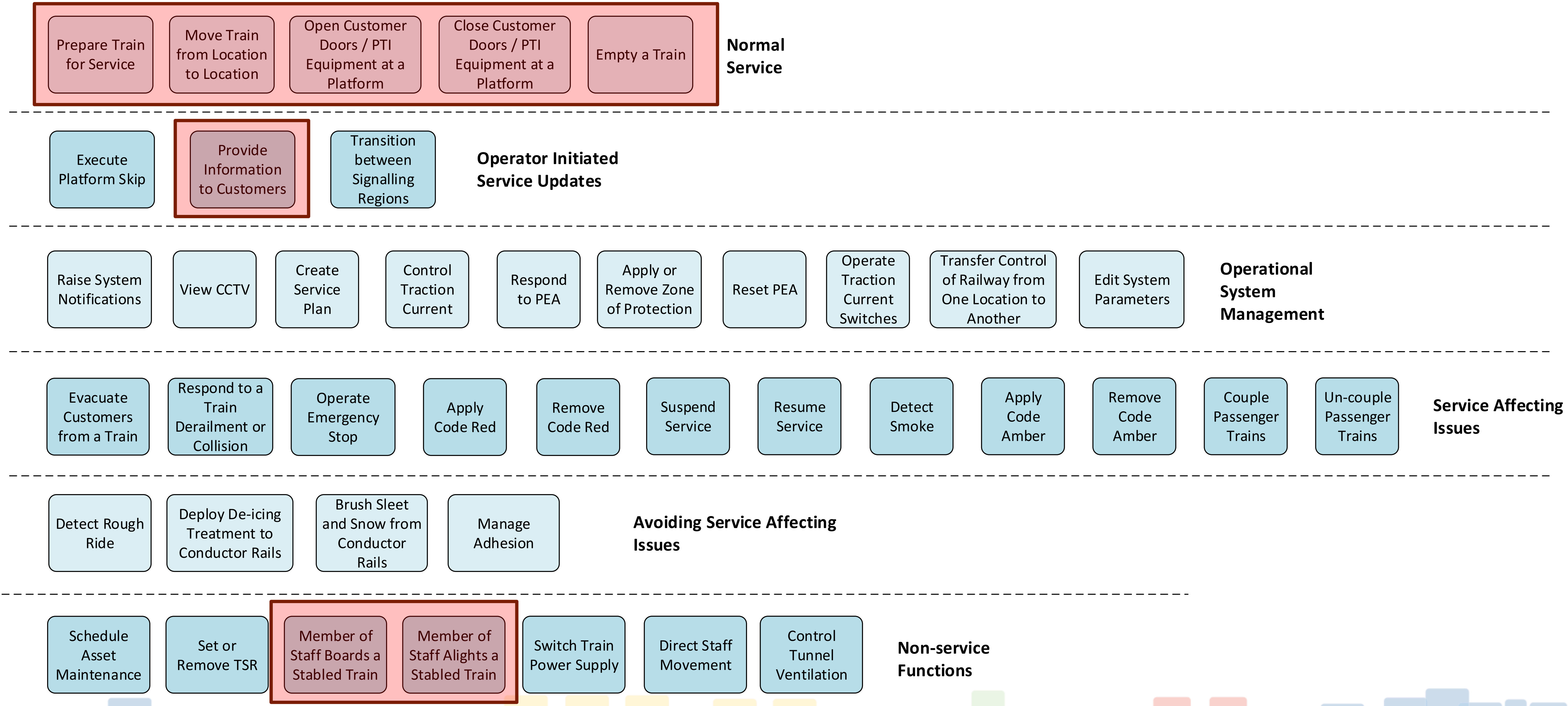
Exceptions

1. Confirmation that the train has stopped in the correct location has not been provided.
2. Train door fails to open.
3. Access to the platform obstructed.
4. Prerequisite conditions (Stopping location, PTI Equipment, etc) not achieved.

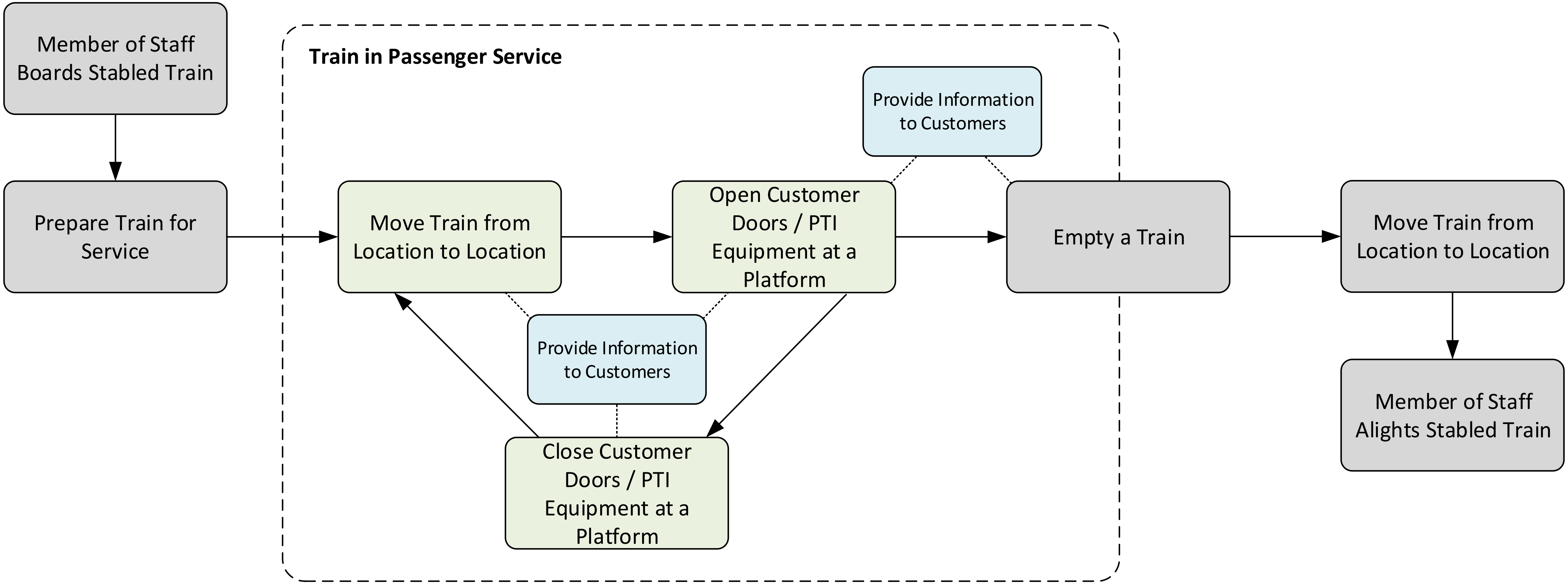
Specific Applications

1. Manually open doors from inside the train.
2. Manually open doors from the platform.
3. Train automatically controlled by a signalling system.
4. Train manually controlled under signalling protection.
5. Train manually controlled without signalling protection (signalling available)
6. Train manually controlled with compromised or failed signalling protection
7. Manual movement of train around a depot.
8. Movement of a train in a non-normal direction under signalling protection.
9. Manual movement of a train in a non-normal direction with compromised or failed signalling protection.

Using Functions as Scenario Building Blocks



Using Functions as Scenario Building Blocks



Note: The start and end conditions of linked functions must be compatible!

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Operational Process Execution Diagrams (OPExDs)

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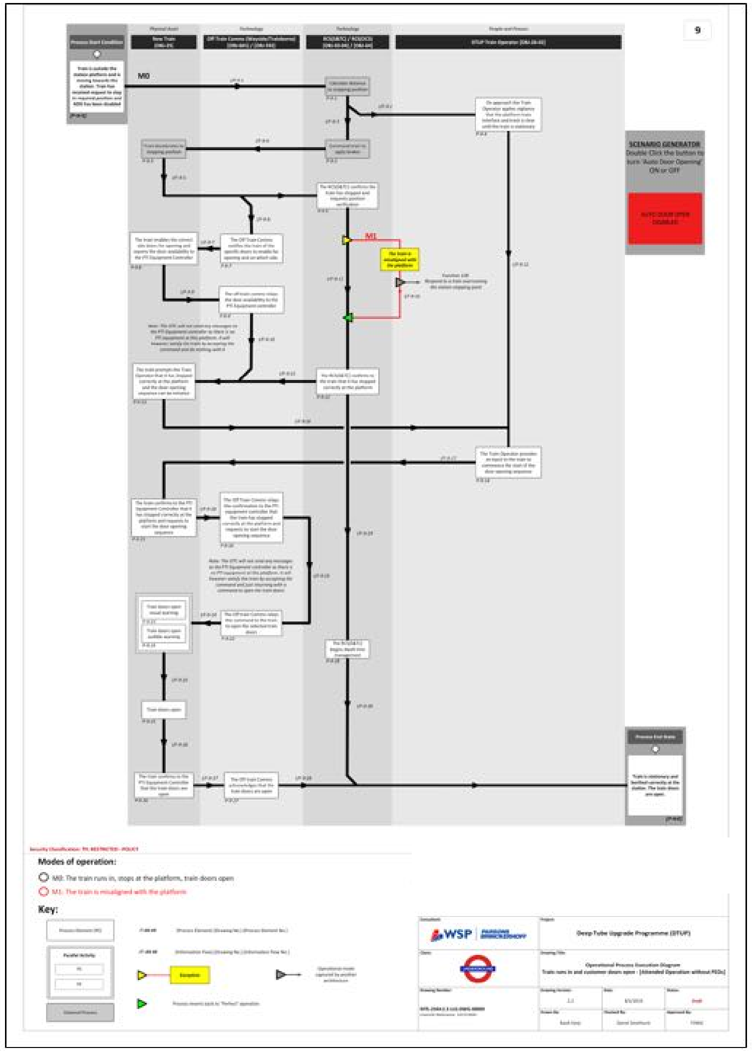
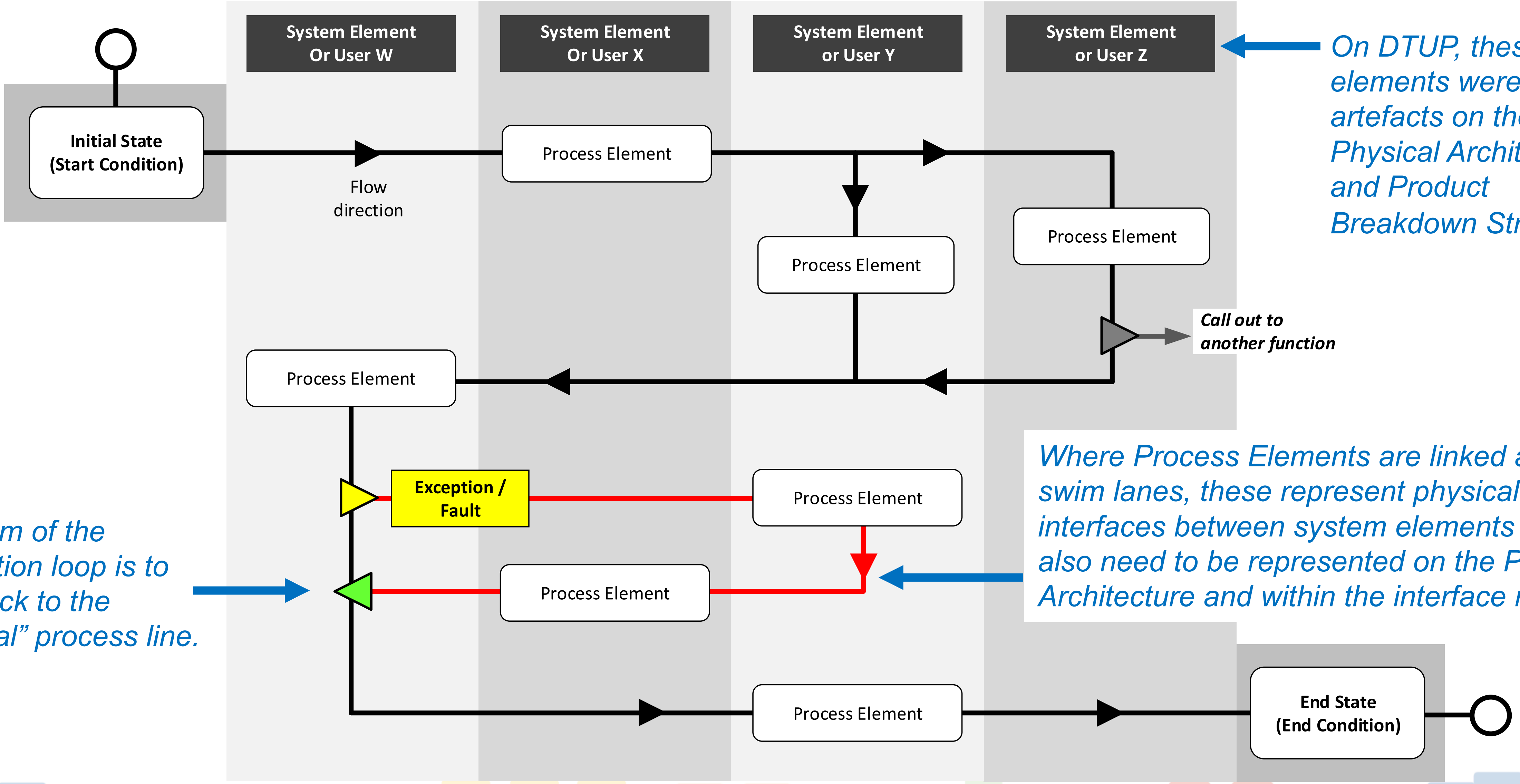
Operational Process Execution Diagrams (OPExDs)



- These diagrams take the functional descriptions and develops “how” each <u>Specific Application</u> of the functions will be achieved by the system.
- Shares similarities with SysML Activity diagrams.
- Developed within DTUP as a way of encouraging engagement with the teams and stakeholders, by communicating this aspect of the system in a common language.

Operational Process Execution Diagrams (OPExDs)

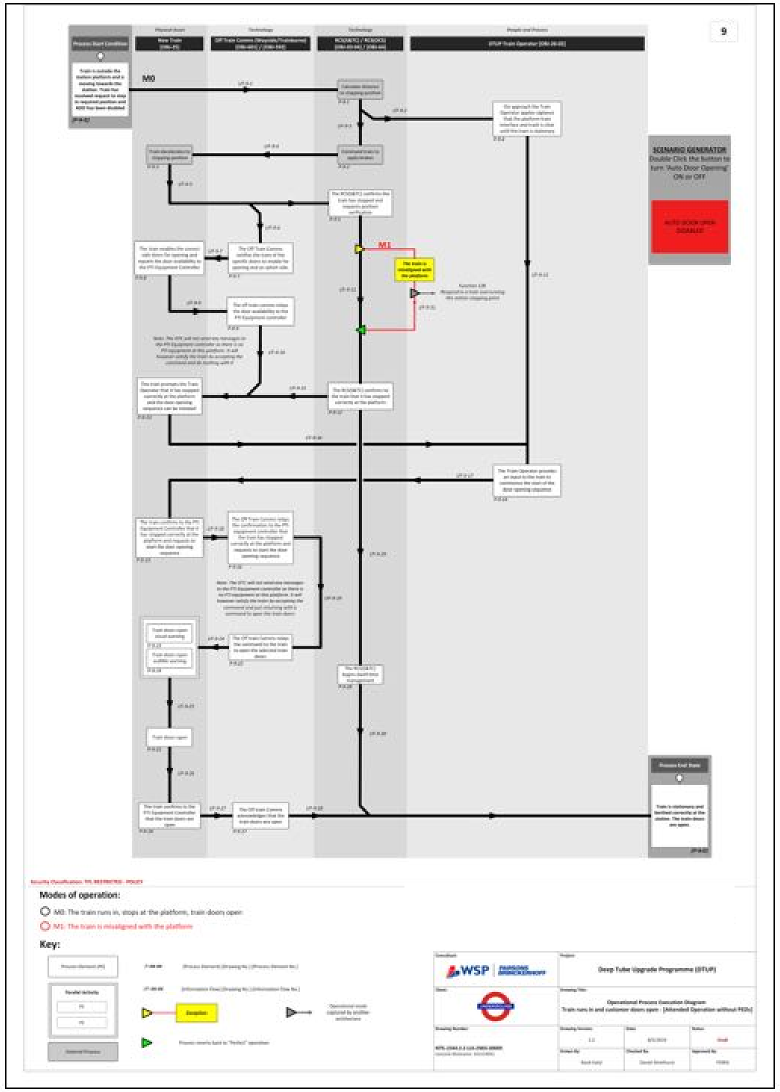


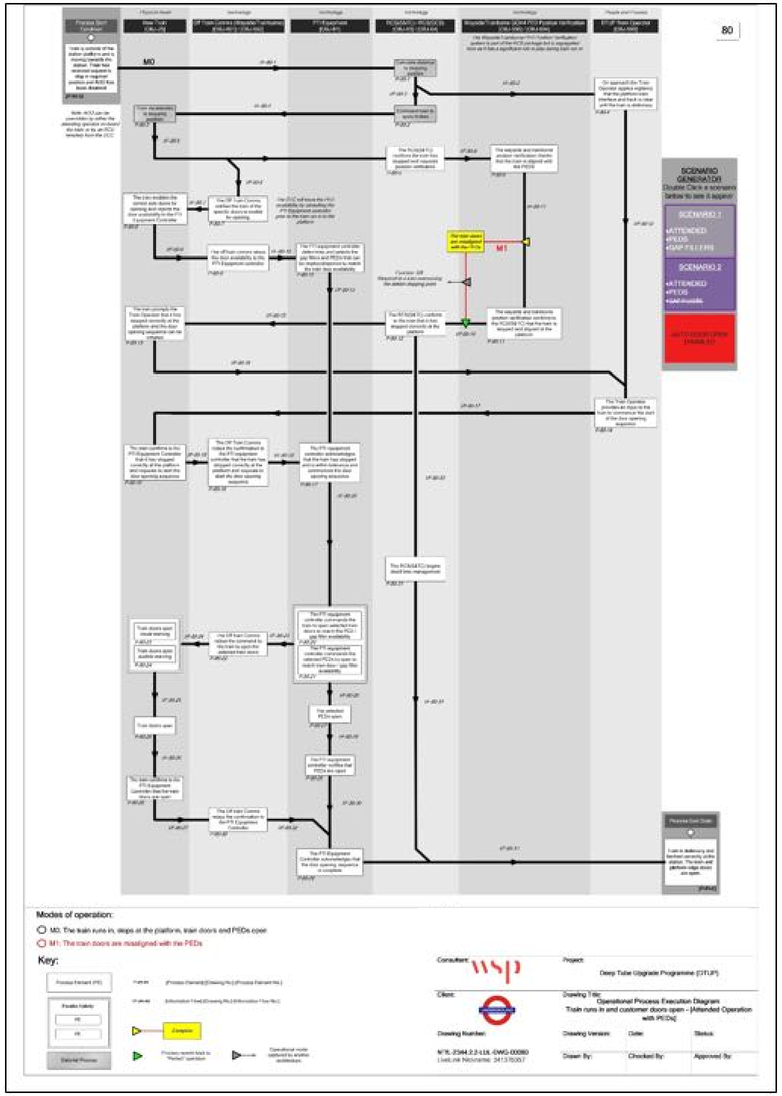
On DTUP, these elements were artefacts on the Physical Architecture and Product Breakdown Structure

Where Process Elements are linked across swim lanes, these represent physical interfaces between system elements that also need to be represented on the Physical Architecture and within the interface register.

The aim of the exception loop is to get back to the "normal" process line.

Operational Process Execution Diagrams (OPExDs)





Satisfaction Matrices

Specific Applications for the respective function.

Process Steps for the respective function.

Exceptions for the respective function.

Requirements in DOORS that satisfy each Process Step for each Specific Application.

		Specific Applications				
		Train automatically controlled by the DTUP signalling system (Attended)	Train manually controlled under DTUP signalling protection	Train manually controlled without DTUP signalling protection (signalling available)	Train manually controlled without legacy signalling protection (signalling available)	Train manually controlled under legacy signalling protection
Process Steps	Identify location(s), and availability, of Trains fitted with de-icing equipment **[SysFn-917]**	SYS-9964 (MS 6+) SYS-9997 (MS 6+) SYS-4460 (MS 2+) SYS-3531 (MS 6+)	SYS-9964 (MS 6+) SYS-9997 (MS 6+) SYS-4460 (MS 2+) SYS-3531 (MS 6+)	SYS-9964 (MS 6+) SYS-9997 (MS 6+) SYS-4460 (MS 2+) SYS-3531 (MS 6+)	SYS-4460 (MS 2+)	SYS-4460 (MS 2+)
	Monitor de-icing fluid levels on board de-icing Trains **[SysFn-919]**	SYS-4515 (MS 2+) SYS-8562 (MS 2+) SYS-8668 (MS 2+)	SYS-4515 (MS 2+) SYS-8562 (MS 2+) SYS-8668 (MS 2+)	SYS-4515 (MS 2+) SYS-8562 (MS 2+) SYS-8668 (MS 2+)	SYS-4515 (MS 2+) SYS-8562 (MS 2+) SYS-8668 (MS 2+)	SYS-4515 (MS 2+) SYS-8562 (MS 2+) SYS-8668 (MS 2+)
	Allocate relevant de-icing mission to de-icing Train **[SysFn-920]**	SYS-9564 (MS 6+) SYS-4329 (MS 6+) SYS-4567 (MS 6+) SYS-4402 (MS 2+)	SYS-9564 (MS 6+) SYS-4329 (MS 6+) SYS-4567 (MS 6+)	SYS-9564 (MS 6+) SYS-4329 (MS 6+) SYS-4567 (MS 6+)		
	Determine if Train has reached the location it needs to start de-icing **[SysFn-921]**					
	Instruct Train to start dispensing de-icing fluid **[SysFn-922]**	SYS-4469 (MS 2+) SYS-8849 (MS 6+) SYS-9068 (MS 6+) SYS-9970 (MS 2+)	SYS-4469 (MS 2+) SYS-8849 (MS 6+) SYS-9068 (MS 6+) SYS-9970 (MS 2+)	SYS-4469 (MS 2+) SYS-8849 (MS 6+) SYS-9068 (MS 6+) SYS-9970 (MS 2+)	SYS-4469 (MS 2+) SYS-9970 (MS 2+)	SYS-4469 (MS 2+) SYS-9970 (MS 2+)
	Determine if Train has reached the location it needs to stop de-icing **[SysFn-923]**					
	Instruct Train to stop dispensing de-icing fluid **[SysFn-924]**	SYS-8849 (MS 6+) SYS-8850 (MS 7+) SYS-8847 (MS 6+) SYS-1611 (MS 6+) SYS-9068 (MS 6+) SYS-9970 (MS 2+) SYS-9960 (MS 6+) SYS-8835 (MS 6+)	SYS-8849 (MS 6+) SYS-8850 (MS 7+) SYS-8847 (MS 6+) SYS-1611 (MS 6+) SYS-9068 (MS 6+) SYS-9970 (MS 2+) SYS-9960 (MS 6+) SYS-8835 (MS 6+)	SYS-8849 (MS 6+) SYS-8850 (MS 7+) SYS-8847 (MS 6+) SYS-1611 (MS 6+) SYS-9068 (MS 6+) SYS-9970 (MS 2+) SYS-9960 (MS 6+) SYS-8835 (MS 6+)	SYS-9970 (MS 2+)	SYS-9970 (MS 2+)
	Make a record of the area that has been treated **[SysFn-918]**	SYS-3455	SYS-3455	SYS-3455		
	Monitor de-icing fluid levels on board de-icing Trains **[SysFn-925]**	SYS-4515 (MS 2+) SYS-8562 (MS 2+)	SYS-4515 (MS 2+) SYS-8562 (MS 2+)	SYS-4515 (MS 2+) SYS-8562 (MS 2+)	SYS-4515 (MS [illegible] SYS-8562 (MS 2+)	[illegible] SYS-8562 (MS 2+)
Exceptions	Train is not in motion	SYS-9540 (MS 2+) SYS-9969 (MS 2+)	SYS-9540 (MS 2+) SYS-9969 (MS 2+)	SYS-9540 (MS 2+) SYS-9969 (MS 2+)	SYS-9540 (MS 2+) SYS-9969 (MS 2+)	SYS-9540 (MS 2+) SYS-9969 (MS 2+)
	Train is operating in tunnel sections of the line	SYS-9540 (MS 2+) SYS-9968 (MS 2+)	SYS-9540 (MS 2+) SYS-9968 (MS 2+)	SYS-9540 (MS 2+) SYS-9968 (MS 2+)	SYS-9540 (MS 2+) SYS-9968 (MS 2+)	SYS-9540 (MS 2+) SYS-9968 (MS 2+)
	Failure/inoperability of de-icing system or insufficient de-icing fluid levels on a specific Train					

Accessibility of SE

Accessibility of SE Techniques to Non-SE Stakeholders

SE Practitioner Perspective

Formalised Patterns
Modelling Languages
Formal System Model

Drives / Governs

Client / Stakeholder / Non-SE Perspective

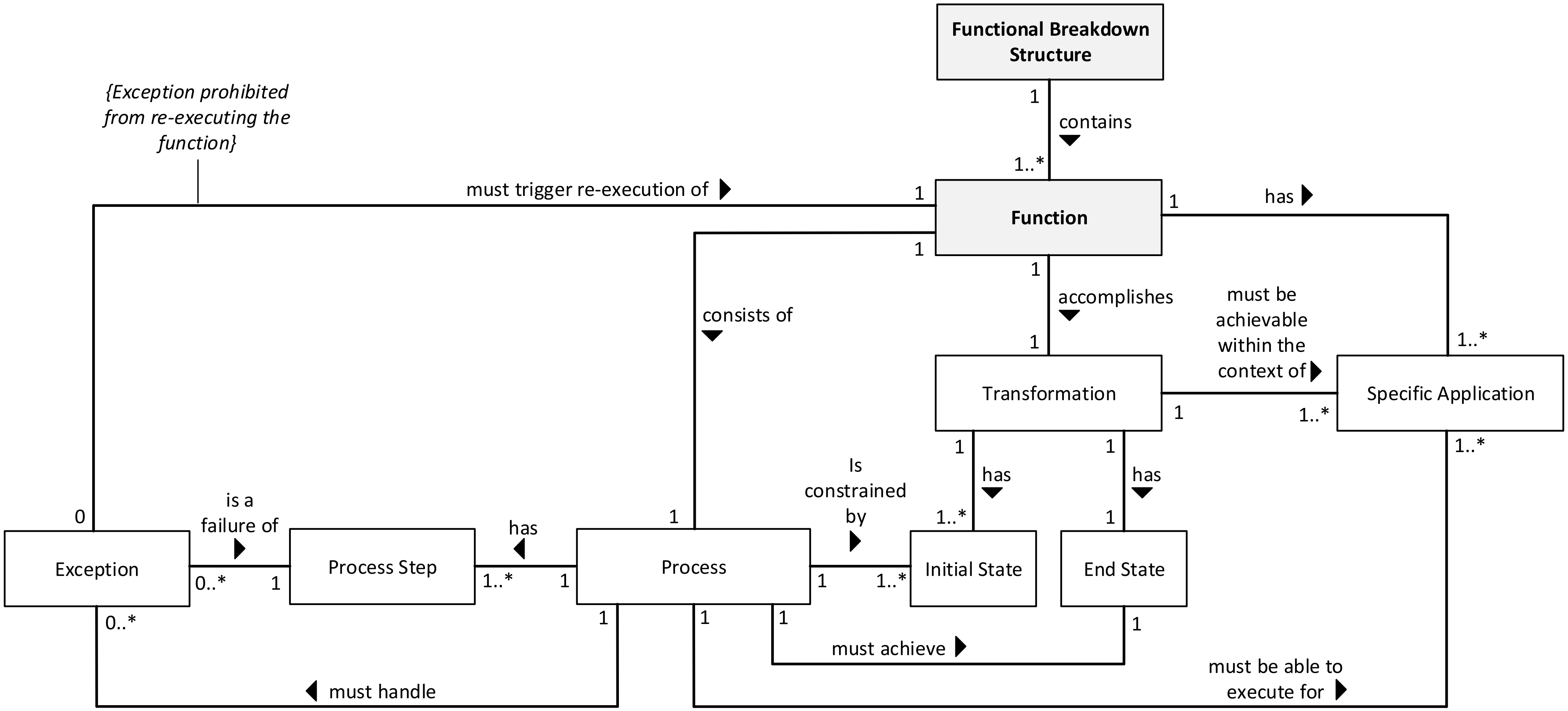
Rich Pictures and Visualisations
Natural Language Output
Communication and Collaboration Tools

Achieving good balance here (which depends on the maturity of SE in the particular industry) promotes good engagement with stakeholders and hence better quality information that can be fed back into the model.

The **"Picture This!"** paper by John Welford (et al) discusses the importance of effective visualisations with respect to SE outputs.

"Picture This!", provoking stakeholder engagement through diagrammatic iteration - Welford (et al)
http://www.extuitive.co.uk/papers/PictureThis.pdf

Functional Description Pattern



In Conclusion…

In Conclusion…

A custom, but repeatable and scalable methodology was implemented on the Deep Tube Upgrade Programme to develop a functional model and the programme's functional requirements.

The methodology was particularly effective at:

- Promoting good collaboration and cooperation between the teams.
- Providing a common language to facilitate a common understanding of the system across the various disciplines.
- Providing a focus on "what happens when things go wrong".
- Identifying and plugging gaps in the OpCon and User Requirements.
- Helping the Programme consider future operating modes.

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Questions

About the Authors

Nathan Everett (Lead Author) was a Senior Systems Integration Consultant within WSP's UK Rail business who was embedded with the Deep Tube Upgrade Programme (DTUP) team at London Underground between June 2017 and April 2019. Nathan is a Chartered Engineer and has more than 20 years' experience practicing all phases of systems engineering from requirements generation through system verification and validation in the automotive, aerospace, and rail industries. In addition to DTUP, he has been involved with the design and development of automatic transmissions, requirements management solutions, hybrid electric vehicles, custom database solutions, landing gear actuation systems, cockpit control panels, and holds two U.S. patents.

Luke Fischer is an Associate Systems Engineer within WSP's UK Rail business, responsible for delivering systems engineering and integration services to clients in the railway sector. Luke is an ASEP and Incorporated Engineer with over thirteen years of railway engineering experience, and has worked on large multi-disciplinary railway projects such as the DTUP, Midland Main Line Upgrade Programme, the Northern Hub Programme, the Thameslink Programme, Crossrail (One) and Heathrow Terminal Five (Rail Station). Luke was a member of the System Integration team on DTUP between Nov 2013 and April 2018.

Michael Coultharde-Steer was the Lead Operational Delivery Manager at London Underground (LU) / TfL. He has 18 years of experience with LU, spending seven years in front-line operations, first on stations, and then as a duty manager (Trains). For the past 11 years he has worked as an operational representative alongside the engineering and project management teams of several major railway upgrades (including the Victoria line upgrade, and DTUP), providing specialist operational knowledge, representing the interests of the end-user, and liaising with front-line operational staff on behalf of the project teams.

Thanks and additional credits

The authors would like to thank the following people for assisting in / facilitating the development and delivery of this paper and presentation:

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