Project FALCON

Automatic Load Transfer

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Contents

Executive Summary 12

1 Project Introduction 14

2 Introduction to Technique Trial 16

2.1 Presentation of Learning 17

2.2 Overview of technique 17

3 Design, Construction and Commissioning 21

3.1 Introduction to Technique trial network sections 22

3.2 Initial assessment of required switching locations 23

3.3 Overview of as-installed equipment 23

3.4 Key Learning from Implementation 25

4 FALCON ALT Assessment Framework 28

4.1 Overview of the FALCON ALT assessment framework 29

4.2 Overview of load flow modelling 29

4.3 Alternate NOP identification approaches 32

4.4 Investigation of variation of preferred NOPs across the year 36

4.5 Dependency on load model accuracy 39

5 Identified Alternative NOPs 40

5.1 Method 1 Assessment of Underground Trial Network 41

5.2 Method 1 Assessment of Overhead Trial Network 46

5.3 Method 2 Assessment of Overhead Trial Network 49

5.4 Method 2 assessment on underground trial network 57

5.5 Generalised learning from the alternate NOP assessment process 61

6 Trial Results and Discussion 62

6.1 Validation 63

6.2 Feeder current comparison 63

6.3 Modelled trial benefits 75

7 Cross-technique Comparison 83

8 Conclusions and Recommendations 88

Appendices 92

A References 93
B Initial Learning Objectives 97
C Literature review 98
D Method 1 identified NOPs across the year. 101
E Variation in preferred NOP positions across the year for cable network using method 2 analysis. 102
F Validation 109
G Effect of feeder load distribution on network losses following changes to network configuration 113
H Method 1 : Monte-Carlo calculation of NOP points 115
I Method 1 : OHL Trial Network NOP location 116
J Method 1 : Cable trial HV Diagrams 117
K Method 1 : Cable Trial Network NOP location 120
L Method 1 : OHL Seasonal Switching Pattern 121
M Method 1 : Cable Seasonal Switching Pattern 124
N Method 2 : Cable NOP location determination 126
O Method 1: OHL feeder utilisation results 129
P Method 1: Cable feeder utilisation results 134
Q Method 2: OHL feeder utilisation results 140
R Method 2: Cable feeder utilisation results 145
S Results summary 151

Figures

Figure 1: Stylised representation of the ALT underground trial network 22
Figure 2: Stylised representation of the ALT overhead trial network 22
Figure 3 : Installed switchgear actuators. 24
Figure 4 : Installed switchgear CT's. 25
Figure 5: Representation of FALCON ALT assessment framework 29
Figure 6: IPSA model for the Newport Pagnell and Marlborough Street substations 30
Figure 7: IPSA model for the Newport Pagnell and Marlborough Street substations 31
Figure 8 : NOP movement to balance feeder utilisation in the presence of a) load only, b) load and low value generation and c) load and high value generation. 35
Figure 9: Preferred open points for a Winter Sunday on the Cable Network around Hainault Avenue 38
Figure 10 : Stylised network diagram showing changes for 22-29 May – initial test configuration 42
Figure 11: Stylised network diagram showing changes for 17-24 Jun - Configuration 1 43
Figure 12: Stylised network diagram showing changes for 17-24 Jun - Configuration 2 44
Figure 13: Graphical representation of potential NOP switching pattern for cable 45
Figure 14: Ideal preferred configuration 46
Figure 15: Practical preferred configuration 47
Figure 16: Graphical representation of potential NOP switching pattern with full generation 48
Figure 17 : Possible Open Point locations on OHL trial network using Method 2 analysis 49
Figure 18 : Percentage Feeder utilisation of NR05 and WS03 over 10 typical days with calculated open point position 52
Figure 19: Graphical representation of potential NOP switching pattern for OHL with full generation 53
Figure 20: Graphical representation of potential NOP switching pattern for OHL with full generation 54
Figure 21: Stylised network diagram showing changes for network test starting 02/06/2015 56
Figure 22: Illustration of possible NOP location for feeder utilisation balance on Cable trial network 58
Figure 23: NOP spread points for Kara Food, Wolverton

Rd and Hainault 59
Figure 24: Stylised network diagram showing changes for network test starting 02/06/2015 60
Figure 25: Measured and estimated feeder utilisation of MS07 and NP08 over week 1 65
Figure 26: Measured and estimated feeder utilisation of MS07 and NP08 over week 2 65
Figure 27: Measured and estimated feeder utilisation of WS03 and NR05 over week 1 67
Figure 28: Measured and estimated feeder utilisation of WS03 and NR05 over week 2 68
Figure 29: Feeder utilisation for week 1 (WS03/NR05) 69
Figure 30: Feeder utilisation for week 2 (WS03/NR05) 70
Figure 31: Feeder utilisation for week 1 (NR08/WS06) 71
Figure 32: Feeder utilisation for week 2 (NR08/WS06) 71
Figure 33 Feeder utilisation with pre-existing NOP between MS07 and NP08 73
Figure 34 Feeder utilisation with optimised NOP between MS07 and NP08 73
Figure 35 : Voltage profile along Newton Rd feeder 6 showing changes to voltage as the feeder is re-configured under method 1 81
Figure 36 : Voltage profile along Winslow feeder 6 showing changes to voltage as the feeder is re-configured under method 1 81
Figure 37: Graphical representation of potential NOP switching pattern with full generation 101
Figure 38: Graphical representation of potential NOP switching pattern with full generation 102
Figure 39 : NOP spread points for Kara Food, Wolverton Rd and Hainault 108
Figure 40 :Cable Network ratio (Ref#1/Ref#4)/(Ref#2/Ref#3) for each half hour slot over trial period 111
Figure 41 :OHL Network ratio (Ref#1/Ref#4)/(Ref#2/Ref#3) for each half hour slot over trial period 111
Figure 42: Validation through comparison of recorded and calculated feeder data 112
Figure 43 : Example showing how results from a poorly conditioned model would be picked up. 113
Figure 44: HV diagram showing Intermediate NOP configuration applied during 22-29th May 2014 117
Figure 45: HV diagram showing Configuration 2 – ideal preferred configuration 118
Figure 46: HV diagram showing configuration 1 -

practicable preferred configuration applied during 17-24 June 2014 119
Figure 47: Feeder utilisation with pre-existing NOP between MS10 and MS01 (No.5 Wolverton Rd) 126
Figure 48: Feeder utilisation with optimised NOP between MS10 and MS01 (No.5 Wolverton Rd) 126
Figure 49: Feeder utilisation with pre-existing NOP between MS07 and NP07 (No.6 Hainault) 127
Figure 50 Feeder utilisation with optimised NOP between MS07 and NP07 (No. Hainault) 127
Figure 51: Feeder utilisation with pre-existing NOP between NP09 and NP08 (No. 7 Ackerman) 128
Figure 52: Feeder utilisation with optimised NOP between NP09 and NP08 (No. 7 Ackerman) 128
Figure 53: Measured and estimated feeder utilisation of WS03 and NR05 over week 1 129
Figure 54: Measured and estimated feeder utilisation of WS03 and NR05 over week 2 129
Figure 55: Measured and estimated feeder utilisation of WS06 and NR08 over week 1 130
Figure 56: Measured and estimated feeder utilisation of WS06 and NR08 over week 2 130
Figure 57 : Measured and estimated feeder utilisation of WS03 and WS06 over week 1 131
Figure 58 : Measured and estimated feeder utilisation of WS03 and WS06 over week 2 131
Figure 59 : Measured and estimated feeder utilisation of NR08 and NR05 over week 1 132
Figure 60 : Measured and estimated feeder utilisation of NR08 and NR05 over week 2 132
Figure 61 : Measured and estimated feeder utilisation of NR04 and NR05 over week 1 133
Figure 62 : Measured and estimated feeder utilisation of NR04 and NR05 over week 2 133
Figure 63: Measured and estimated feeder utilisation of MS07 and NP08 over week 1 134
Figure 64: Measured and estimated feeder utilisation of MS07 and NP08 over week 2 134
Figure 65: Measured and estimated feeder utilisation of MS10 and NP09 over week 1 135
Figure 66: Measured and estimated feeder utilisation of MS10 and NP09 over week 2 135
Figure 67 : Measured and estimated feeder utilisation of MS10 and NP03 over week 1 136

Figure 68 : Measured and estimated feeder utilisation of MS10 and NP09 over week 2 136
Figure 69 : Measured and estimated feeder utilisation of NP07 and NP03 over week 1 137
Figure 70 : Measured and estimated feeder utilisation of NP07 and NP03 over week 2 137
Figure 71 : Measured and estimated feeder utilisation of MS10 and MS01 over week 1 138
Figure 72 : Measured and estimated feeder utilisation of MS10 and MS01 over week 2 138
Figure 73 : Measured and estimated feeder utilisation of MS07 and NP07 over week 1 139
Figure 74 : Measured and estimated feeder utilisation of MS07 and NP07 over week 2 139
Figure 75: Feeder utilisation for week 1 (WS03/NR05) 140
Figure 76: Feeder utilisation for week 2 (WS03/NR05) 140
Figure 77: Feeder utilisation for week 1 (NR08/WS06) 141
Figure 78: Feeder utilisation for week 2 (NR08/WS06) 141
Figure 79 : Measured and estimated feeder utilisation of WS03 and WS06 over week 1 142
Figure 80 : Measured and estimated feeder utilisation of WS03 and WS06 over week 2 142
Figure 81 : Measured and estimated feeder utilisation of NR08 and NR05 over week 1 143
Figure 82 : Measured and estimated feeder utilisation of NR08 and NR05 over week 2 143
Figure 83 : Measured and estimated feeder utilisation of NR04 and NR05 over week 1 144
Figure 84 : Measured and estimated feeder utilisation of NR04 and NR05 over week 2 144
Figure 85 : Feeder utilisation with pre-existing NOP between MS07 and NP08 145
Figure 86 : Feeder utilisation with optimised NOP between MS07 and NP08 145
Figure 87 : Feeder utilisation with pre-existing NOP between MS10 and NP09 146
Figure 88 : Feeder utilisation with optimised NOP between MS10 and NP09 146
Figure 89 : Feeder utilisation with pre-existing NOP between MS10 and NP03 147
Figure 90 : Feeder customer number with optimised NOP between MS10 and NP03 147
Figure 91 : Feeder utilisation with pre-existing NOP between NP07 and NP03 148

Figure 92 : Feeder customer utilisation with optimised NOP between NP07 and NP03 148
Figure 93 : Feeder utilisation with pre-existing NOP between MS10 and MS01 149
Figure 94 : Feeder customer utilisation with optimised NOP between MS10 and MS01 149
Figure 95 : Feeder utilisation with pre-existing NOP between MS07 and NP07 150
Figure 96 : Feeder customer utilisation with optimised NOP between MS10 and MS01 150

Tables

Table 1:Sample analysis days 37
Table 2: Trial periods and corresponding actual NOP configuration 44
Table 3: Trial periods and corresponding actual NOP configuration 47
Table 4: Possible combinations of OHL NOPs 50
Table 5: Trial periods and corresponding actual NOP configuration 56
Table 6: Possible locations and combination 57
Table 7: Trial periods and corresponding actual NOP configuration 60
Table 8: Comparison of calculated and measured peak feeder currents during trial periods for cable network 64
Table 9: Comparison of calculated and measured peak feeder currents during trial periods for OHL network 66
Table 10: Method 2 Feeder current validation for the overhead line Network 69
Table 11: Method 2 Feeder current validation for the cable Network 72
Table 12: Method 1 - Calculated highest feeder utilisations for trial period week 2 for overhead line network 75
Table 13: Method 2 - Calculated highest feeder utilisations for trial period week 2 for overhead line network 76
Table 14: Method 1 - Calculated highest feeder utilisations for trial periods 17-24 Jun 2014 for Cable Network 77
Table 15: Method 2 - Calculated highest feeder utilisations for trial periods for Cable Network 77
Table 16: Method 2 maximum feeder utilisation 78
Table 17 : Comparison of calculated losses variation under trial configuration 78
Table 18 : Comparison of benefit gains with seasonal NOP variation. 79
Table 19: Comparison of minimum bus voltage variation 80
Table 20: Cross-technique comparison of impact. 84
Table 21 : Previously undertaken ALT validation 100
Table 22 : Summary of identified changes for UG trials network on typical weekends 103
Table 23:Summary of identified changes for UG trials network on typical weekdays 104

Table 24: Within-day NOP variation on typical weekends 106
Table 25 : Within-day NOP variation on typical weekdays 107
Table 26: key measurements and calculations arising from trials 110
Table 27 : Winter Sunday – summary of switching schedule 121
Table 28 : Spring Sunday – summary of switching schedule 121
Table 29 : Summer Sunday – summary of switching schedule 121
Table 30 : High Summer Sunday – summary of switching schedule 121
Table 31 : Autumn Sunday – summary of switching schedule 122
Table 32 : Winter Wednesday – summary of switching schedule 122
Table 33 : Spring Wednesday – summary of switching schedule 122
Table 34 : Summer Wednesday – summary of switching schedule 122
Table 35 : High Summer Wednesday – summary of switching schedule 123
Table 36 : Autumn Wednesday – summary of switching schedule 123
Table 37: Method 1 - Calculated highest feeder utilisations for trial period week 1 for overhead line network 151
Table 38: Method 1 - Calculated highest feeder utilisations for trial period week 2 for overhead line network 151
Table 39: Method 1 - Calculated highest feeder utilisations for trial periods 15-20 May 2014 for Cable network 152
Table 40: Method 1 - Calculated highest feeder utilisations for trial periods 17-24 Jun 2014 for Cable Network 152
Table 41: Method 2 - Calculated highest feeder utilisations for trial period week 1 for overhead line network 152
Table 42: Method 2 - Calculated highest feeder utilisations for trial period week 2 for overhead line network 152

Table 43: Method 2 - Calculated highest feeder utilisations for trial periods for Cable network 153
Table 44: Method 2 - Calculated highest feeder utilisations for trial periods for Cable Network 153
Table 45: Method 1 comparison of calculated total losses of OHL Network with configurations in trial period (MWh) 153
Table 46: Method 1 comparison of calculated total losses of Cable Network with configurations in trial period (MWh) 153
Table 47 : Method 2 comparison of calculated total losses of OHL Network with configurations in trial period (MWh) 153
Table 48 : Method 2 comparison of calculated total losses of Cable Network with configurations in trial period (MWh) 154
Table 49 : Comparison of losses variation 155
Table 50 : Method 1- Summary of calculated minimum voltages (kV) on overhead line network 155
Table 51 : Method 1 -Summary of calculated minimum voltages (kV) on cable line network 156
Table 52 : Method 2- Summary of calculated minimum voltages (kV) on overhead line network 156
Table 53: Method 2 -Summary of calculated minimum voltages (kV) on cable line network 156
Table 54: Method 1- customer numbers of OH network with different configurations 156
Table 55: Method 1- Customer numbers of cable network with different configurations 156
Table 56:Method 2- customer numbers of OH network with different configurations 157
Table 57: Method 2- Customer numbers of cable network with different configurations 157
Table 58 : Comparison of customer number variation 157
Table 59: Method 1 –Calculated OHL Network switching benefits 159
Table 60: Method 1 –Calculated Cable Network switching benefits 159
Table 61 :Method 2 –Calculated OHL Network switching benefits 160
Table 62 :Method 2 –Calculated Cable Network switching benefits 160
Table 41: Comparison of benefit gains 161

Executive Summary

With the growth in all types of low carbon generation, such as wind and solar photovoltaic (PV), and the introduction of new demand technologies such as electric vehicles (EVs) and heat pumps, Western Power Distribution's (WPD) electricity network is expected to see unprecedented swings between peaks and troughs of energy usage in localised areas.

WPD's Project FALCON has examined a range of innovative alternatives to conventional reinforcement that might be used to mitigate the impact of such energy usage. This was undertaken firstly through physically trialling four engineering and two commercial techniques. Secondly, innovative alternatives where examined through building and operating a software tool. This tool: models the real network under a range of energy use scenarios out to 2050; identifies network constraints that arise over time; employ the studied techniques to mitigate constraints; and assesses impact and benefit.

This report is one of a series describing the engineering technique trials, and focuses on automatic load transfer (ALT) within networks. The ALT engineering technique trial within the FALCON project examined the practice of changing Normal Open Points (NOP) and demonstrated and explored the potential to relieve technical constraints on the 11kV network. This report looked at dynamically shifting load between HV feeders by altering normal open points on two distinct trial areas of network, based on the prevailing network loads.

Recommendations based on this technique are:

- It is recommended that the FALCON NOP positions are considered for adoption on the trial network, subject to review and mitigation of customer number changes.
- ALT appears to offer potential to reduce losses through a one-off/occasional re-assessment of NOP position across the network. Further work would be required to complete specification of cross-network data requirements, and consolidate modelling algorithms for bulk network assessment purposes. It is recommended that the potential of such an exercise is further considered.
- ALT also appears to offer potential to optimise a network that is approaching thermal limits. It is recommended that a candidate portion of network could be assessed using this technique to trial actual solution provision, where network is currently approaching/is at limits.

Key findings from the Automatic Load transfer (ALT) trials are that:

- Distinct algorithms were required to optimise for different criteria, illustrating the complexity inherent in modelling for ALT. This also demonstrated that ALT benefits are not all simultaneously realisable. In this report two methods of calculating open point location were used;
  - method 1 looked at minimising losses and

  - method 2 looked at increasing capacity headroom.

Improvements in 11kV capacity (at first branch out of the primary) of up to 12 percentage points are possible. These improvements are dependent on the algorithm used, method 2 gave superior results to method 1.

- Improvements of up to 12% of losses, using method 1, are also possible.
- Voltage improvement was also calculated under method 1. This is more noticeable on a rural overhead line Network, and overall was marginal in magnitude.
- Customer numbers per feeder varied consequentially according to the algorithms developed to improve losses/voltage, and capacity. Depending on the specific network, potentially more customers are at risk of being impacted by a fault if the Network is reconfigured to reduce losses or increase capacity headroom. This could be simply mitigated through implementation of “along-feeder” staged protection.

It seems possible that much of the improvements that have been indicated from these technique trials could be captured through a one-off adjustment to NOPs, though the trials do indicate that further (more marginal) benefit may be obtained by implementing within day, over the week, and across season changes to NOPs. Where the analysis shows potential variation in switching points (across the day, within week or across seasons) then the potential switching points are closely clustered. It is considered that further load monitoring would have to occur around the indicated switching points to conclude if these additional benefits really existed, and their magnitude relative to the complexity that would be required to capture them.

Whilst networks could be optimised to improve capacity ahead of need, there is no benefit in doing this in preference to optimising for losses/voltage. ALT could be considered as a strategy for improving capacity headroom, but only as feeders approach thermal limits.

SECTION 1

Project Introduction

With the growth in all types of low carbon generation, such as wind and solar photovoltaic (PV), coupled with the introduction of new technologies such as electric vehicles (EVs) and heat pumps, Western Power Distribution's (WPD) electricity network is expected to see unprecedented swings between peaks and troughs of energy usage in localised areas. This expected change in the nature of customer demand and electricity generation will have an impact on networks nationwide and globally, and provides a significant challenge to WPD, and all electricity network operators.

Part of WPDs approach to this challenge has been look at new flexible ways to design, optimise and manage the network in the future. Project FALCON (Flexible Approaches for Low Carbon Optimised Networks) is designed to help answer these questions and is focussed on the Milton Keynes area 11kV network.

In the past, network operators have used conventional reinforcement to deal with constraints. However, this approach can lead to the solution being over engineered to meet only peak demands; it can also be expensive, disruptive and inefficient. In project FALCON, WPD and its partners are trialling alternative techniques and will assess if they are more flexible, cost effective, quicker to deploy and more effective at managing these new demand requirements than conventional reinforcement. The techniques are:

- Dynamic Asset Ratings – Using prevailing weather conditions to run an asset at a rating potentially higher than its name plate to take advantage of, for example, cold temperatures.
- Automatic load transfer – load is redistributed between 11kV feeders.
- Implementation and operation of a meshed (interconnected) 11kV network.
- Deployment of new battery technologies allow the flow of power on the network to be changed as the battery is charged or discharged.
- Demand Response services - the use of localised smaller generation and load reduction services that can be provided in the event of a local constraint.

Central to the project is the Scenario Investment Model (SIM) - a new piece of software being developed to assist long term network planning. The SIM performs load flow analysis for the network for 48 half-hourly periods during the day for different days of the week and different seasons of the year. Predicted load patterns extend as far as 2050. A network planner will operate the SIM to help with planning based on load forecasting. When a network planner is running the SIM and a voltage or thermal problem is found, the SIM will select the techniques that could help resolve the problem and determine how they could be applied to the network. The best solution can be selected using a weighted metric that combines elements such as installation and operating costs, network performance, losses and disruption to customers.

This report presents the work undertaken through project FALCON on the ALT of 11kV network.

SECTION 2

Introduction to Technique Trial

2.1 Presentation of Learning

Learning Objectives originally associated with this technique are listed in Appendix B. Throughout the document, key learning is presented in a box as follows:

LP #	Brief description of learning.

Each piece of trials feedback is referenced as a Learning Point (LP) with a unique number.

2.2 Overview of technique

A large number of circuits at 11kV on WPD distribution networks are run in an 'open ring' configuration. On these circuits, feeders from the same or adjacent primary substations are electrically connected together at the feeder extremity, via a switching device that is normally in the open position. These feeder inter-connection points are referred to as Normal Open Points (NOPs). All loads on such circuits are ordinarily associated and fed from a specified feeder/Primary Substation. It is possible to close these normal open points and create an open point elsewhere on the network (maintaining the open ring nature of the network), and change the feeder/primary substation that a load (or number of loads) are fed from. Routinely this is done under maintenance or fault circumstances.

The positions of NOPs on a mature portion of network have been established for a variety of reasons, including: limiting load/number of customers on a single feeder; managing network voltage; and allowing immediate access for switching purposes. In many instances, these NOPs have been in place for lengthy periods of time (years). As such, their position may no longer be optimal with respect to losses, voltage, and feeder capacity headroom, particularly where incremental growth in load on a network (within authorised supply capacities) has occurred.

Automatic load transfer (ALT) on the 11kV network is the process of changing the state of switching devices on the network to shift the location of the normally open points (NOPs), and cause an improvement in the network's performance. Deliberately changing the open point, and consequentially what loads are supplied from which primary substations, affects the key network parameters of losses, voltage, and capacity headroom.

This technique seeks to change the power flows on the network through alternative NOP locations. However, there are other potential benefits that may be gained when considering automatic load transfer as a more flexible operational tool within an electricity distribution network. These benefits include:

- Active management of network feeding arrangements to maximise utilisation of existing capacity,
- Automated load transfer at peak times,
- Voltage regulation,
- Even load profile of circuits and feeders,

- Even customer number profile to assist with Customer Interruptions (CI) and Customer Minutes Lost (CML),
- Real-time transfer of load or generation across feeders and primary substations,
- A positive impact on Carbon resulting from reduced losses due to more even loading, better voltage regulation and reduced reinforcement.

The implementation of ALT depends on the network configuration and connected load. Network reconfiguration is a highly complex, non-differentiable, constrained, non-linear (due to the on-off nature of the circuit breakers) mixed integer optimization problem, due to the high number of switching elements in a distribution network. Thus, evaluation of all possible configurations is time consuming. In addition, the process behind how benefits can be validated using measured network data on a practical scale taking into account the issue of substation time varying loading uncertainty is complex.

From a theoretical perspective, a network reconfiguration is an optimisation problem that may have different objective functions, such as minimum switching operations, minimum power loss, balanced feeder load balancing, or their combination [1-7] to comply with a set of operational constraints such as bus bar voltage limits, line or cable capacity ratings and fault levels. Generally these methods can be grouped into several categories; classic optimisation techniques [8-11], sensitivities analysis methods [12], knowledge-based heuristic methods [13-16], and Genetic Algorithms [17]. Sensitivities analysis methods and knowledge-based heuristic methods can provide practical results with short computing time but may not be global solutions. Heuristic techniques including “Sequential Switch Opening” [18, 19] and “Branch Exchange” [20, 21] deal with a branch at a time. Sequential switch opening is where all the switches of the network are initially closed forming a meshed network, then, to eliminate network loops, the switches are opened sequentially starting with the switch that has the lowest current (for example). The process is repeated until the network reaches a radial structure. Branch exchange methods are different from sequential switching, the method starts from the initial configuration of the network and performs pairs of open/close switching actions to produce new network topologies while maintaining the radial nature of the system. However, the solution obtained from branch exchange methods depends on the initial configuration.

A summary of literature in this area is shown in Appendix C, which highlights the reference, methodology, test network used, how the load was modelled and how the research was validated.

There are a number of points worth noting with the research published in this area;

- The ALT method chosen needs to be used in conjunction with a network. Some authors have used small test networks such as the IEEE33 or IEEE70 Bus bar model[1]. The advantage of this type of approach is that different methods of finding the

[1] These are standard prescribed models to allow comparative studies to be undertaken

optimal normal open points can be compared easily and because of the prescribed nature of the network the results are repeatable by other researchers. The disadvantage is that only theoretical benefits are obtained and it is not apparent if the advantages claimed can make the transition to a real world situation.

- Some of this research along with other research has used models of sections of Distribution Networks. Using real network data gives a better picture of how the method may be applied to a real life situation, however, it is not always clear what the quality of the data is behind the model. In particular, the load data in a distribution network is rarely monitored in detail at secondary transformer level and therefore a measured value of primary load current is typically divided among the distribution substations based on indicators such as secondary transformer maximum demand indication. This results in a single case of load division between substations with time - which is not representative of a real network where the load at different substations changes with respect to each other over time. The consequence is that this leads to a single representation of the optimum position of the open points. Where the referenced authors have looked at time varying loads, stochastic evaluation considering load uncertainties and load partition with seasonal variation are used.
- Once the optimum location of the open points has been found, it is necessary to validate that the method behind the locations produces the claimed benefits. Within small test networks this typically manifests itself as an academic study, looking at say improvements in losses, between different configurations. For a Network study, the majority of researchers look at theoretical benefits by comparing calculated parameters under different configurations. Measured validation on a Network is difficult to achieve in practice because the load is continually varying and the load prior to changing the configuration may be different to load after changing the configuration making it difficult to look at claimed benefits, such as loss reduction, directly between different network configurations.

LP 1.	There is significant academic and theoretical published work into modelling and optimisation strategies around ALT, but none of these complex strategies can be directly applied to the network without further validation work.

The objectives of the trial were to shift load between HV feeders by altering normal open points on two distinct trial areas of network, based on the prevailing network loads, and explore:

- potential impacts, both benefits and trade-offs, that could be derived from implementing alternative network configurations (normal open points that are different to the pre-existing set);
- various types of impact, including: feeder load balance; feeder utilisation; circuit losses; circuit voltages; and

- potential to schedule changes to normal open points that deliver material net benefits

For the ALT Technique (T2), two areas of network are considered. An underground load transfer trial on 11kV circuits between Marlborough Street and Newport Pagnell Primary Substations, and an overhead trial on circuits between Winslow and Newton Road Primary Substations.

SECTION 3

Design, Construction and Commissioning

3.1 Introduction to Technique trial network sections

Assessment of the ALT technique was carried out within the trial using two distinct sections of network: one underground section; and one (largely) overhead. Schematics of these two sections of network are shown in Figure 1 and Figure 2.

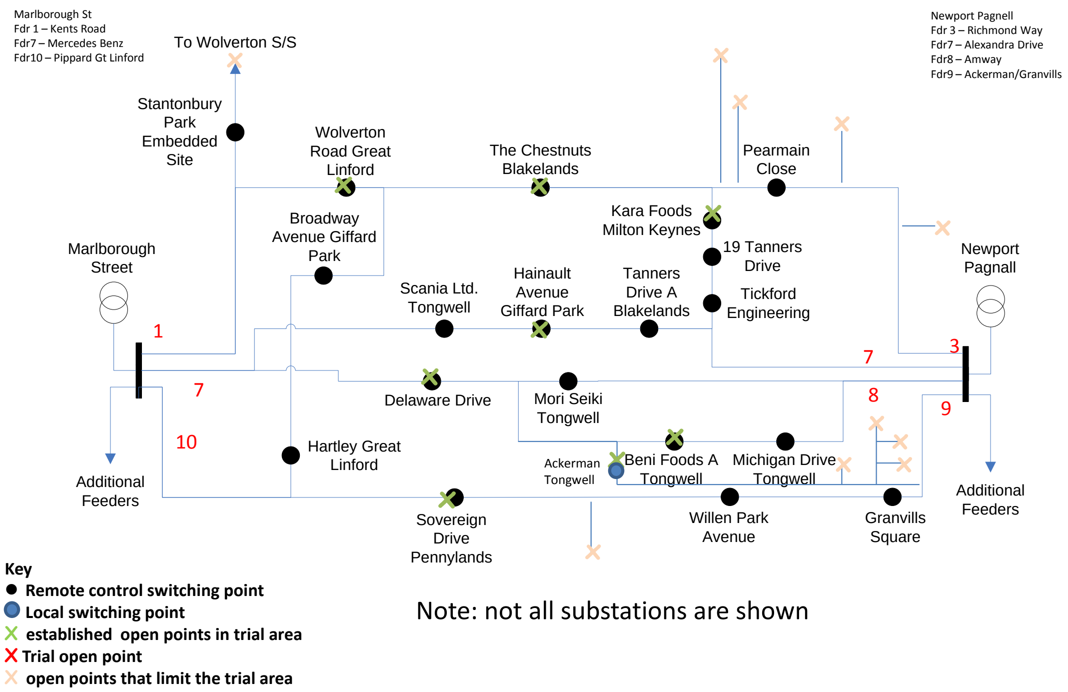

Figure 1: Stylised representation of the ALT underground trial network

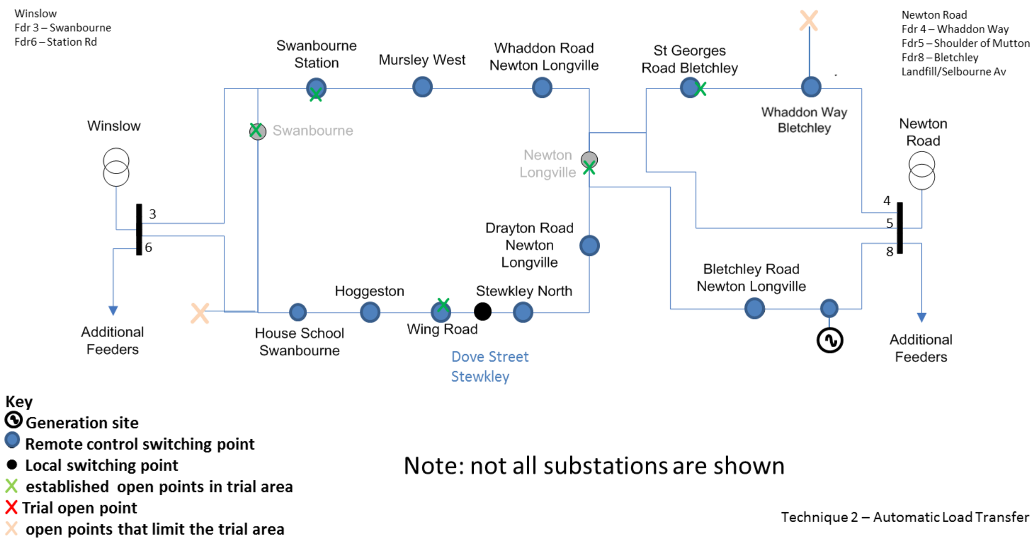

Figure 2: Stylised representation of the ALT overhead trial network

3.2 Initial assessment of required switching locations

In order to meet the project programme milestones it was necessary to order and install additional switchgear and automation devices as soon as possible. Therefore it was required to identify suitable substations to install additional remote control prior to being able to carry out an in depth network study or power system analysis.

To aid the selection of suitable sites a simple power flow study was carried out to identify locations that would allow a variety of different configurations of load and customer numbers by moving open points on the network.

The result of this initial work was the designation of a number of sites as ALT technique trial sites:

- 19 substations across interconnected 11kV circuits between Marlborough Street and Newport Pagnell Primary Substations; and
- 9 substations across interconnected, largely overhead line, circuits between Winslow and Newton Road Primary Substations.

3.3 Overview of as-installed equipment

The installed equipment used in the technique trial comprised of: remote control equipment; current measurement devices; and FALCON Communications Network Equipment.

3.3.1 Remote Control

Underground network

Of the nineteen identified trial sites for the underground network, four of the sites had existing remote control. Of the fifteen sites requiring remote control, some required switchgear changes to facilitate this, others required retrofit of actuators. Details are:

- Five sites either had switchgear that couldn't be equipped with WPD approved remote control devices or were in need of replacement due to age and or condition. Therefore each required a switchgear change to enable remote actuators to be installed (19 Tanners Drive Tongwell, Delaware Drive Milton Keynes, Scania Tongwell, Kara Foods Milton Keynes, Wolverton Road Great Linford). All sites were fitted with Schneider RN2c Ring Main Units (RMUs), complete with remote control actuators and T200 actuator control equipment;
- Four of the sites had Schneider RN series RMUs and Schneider rotary actuators. Control equipment could be, and was retrofitted to this equipment;
- The remaining six sites were fitted with Long and Crawford T3/4 RMUs. After-market linear actuator from Linak (an established solution for automating such RMUs were also fitted, together with actuator control/communications network interface equipment.

Figure 3 shows examples of the two actuator types fitted.

Schneider rotory actuators | Linak linear actuators

Figure 3 : Installed switchgear actuators.

Overhead network

Of the nine sites identified for the trial seven were pole mounted switching sites and two were ground mounted substations.

- Both the ground mounted sites, House School Swanbourne and Hoggeston, had Schneider RN series RMUs and Schneider. Rotatory actuators were retrofitted to this equipment;
- Of the seven pole mounted sites five were existing auto reclosing switches and two were manually operated switches. The two manually operated switches were replaced with Schneider RL27 remote controlled switches. Of the five auto-reclosing switches, two were Schneider PMARs equipped with existing remote control. The remaining three were older Whipp & Bourne reclosers and were not suitable for remote control. These were replaced by new Schneider PMARs.

3.3.2 Current measurement

Initial design work recognised the need to measure actual load as part of assessment of preferred NOP locations. This design work sought to measure current (as a proxy for 11kV power flow) or power directly, and arrangements were made as follows:

- For Schneider RMUs – current measurements from fault passage indicators were utilised. The measurements were logged on the controllers and periodically accessed.
- For Long and Crawford T3/4 sites – CTs were installed in cable boxes, with associated interface units able to signal current flow via the FALCON IP network using Modbus protocol.

Figure 4 : Installed switchgear CT's.

- RL27 switch and N12 recloser using ADVC2 controllers - these devices provide power measurements that can be logged on the controllers and periodically accessed. Voltage transformers and current transformers are factory installed in the HV equipment.

In addition, use was made of pre-existing feeder current measurement arrangements from the Primary substations associated with the technique trial.

3.4 Key Learning from Implementation

3.4.1 Technique-Specific Learning

LP 2.	Low current accuracy of selected along-the-feeder current measurement solution prevented acquisition of some intended data.

- To improve accuracy of the ALT scheme in real-time it is intended to collect phase current flow data from each ALT Site.
- This was possible at some of the Long and Crawford T3/4 sites by installing additional CTs over single phase 11kV cables and interfacing these to the installed FALCON Linak RTUs see Figure 4.

- For the Schneider RN series RMUs, and the installed solution of CTs and measurement board fitted within the RTU, this combination was found through testing to not be suitably accurate at lower current levels to provide any useful information.
- Installation of alternative arrangements is further hampered by existence of 3-phase cables (compared to 3 separate phase cables).
- Given the relative coarseness of the intended along the feeder current/power measurement, reliance was placed on the substation load model that was utilised in modelling (and appropriately validated), and no detailed use of this data was made.

3.4.2 Generalised and Cross-Technique Learning

<table>
<tr>
<td>LP 3.</td>
<td>Significant care should be taken at the planning stage, for “new-to-the-business” communications methods, to ensure that:

proposed remote control of plant is reasonably practicable, given the plant involved;
the proposed communication RTUs/paths are reasonably practicable; and
appropriate interfaces to the network management system can be prepared (given the proposed actuators/RTUs/communication paths).

This may involve extensive testing and engagement with key stakeholders across the business.</td>
</tr>
</table>

- Installation and commissioning of remote control has been significantly more complicated than initially expected.
- Substantial delays were encountered with the progression of switchgear remote control, eventually resulting in a change to utilisation of business-as-usual preferred communications method, with testing of remote control via WiMAX communications recommended as potential follow on work. This was due primarily to:
  - stability issues with the installed Falcon WiMAX-based communications network, and
- Interim utilisation of the business-as-usual preferred communications method required further engineering work for the proposed Linak actuator/RTU solution which has beneficially produced a new standard technique for retrofit of remote control for the business[2].
- A further consequence of the interim utilisation of the business-as-usual preferred communications method is that it is not possible to pass current analogues back to PoF as per initial design intent.

[2] Incoming policy surrounding retrofit of remote control to existing oil-filled RMUs may mean that this has limited application.

LP 4.	A more effective method would have been to create a single solution (e.g. switchgear change) that accommodated an end-to-end tested remote control solution for communications and interface to the network management system.

- Further considerations around this suggested approach include:
  - Package Substation. Is the switchgear part of a package unit i.e. combined RMU, Transformer and LV pillar or are they separate units?
  - Available Space/Clearance. Is it possible just to change the RMU without changing the Transformer and LV Pillar? i.e. is there room within the substation or sufficient clearance between pieces of equipment.
  - Age and Condition. Does the age and or condition of the Transformer and LV pillar present an economic opportunity to change one or both of them also?
  - LV back feeds. Is it possible to hold the substation on LV back feeds during the switchgear change or will a temporary standby generator be required? This may need short interruptions to connect and disconnect the generator.
  - Priority Service Customers. Are there any customers who will need special arrangements in the event of planned interruptions?

SECTION 4

FALCON ALT Assessment Framework

4.1 Overview of the FALCON ALT assessment framework

As previously described, ALT on the 11kV network is the process of changing the state of switching devices on the network to shift the location of the normally open points, and cause an improvement in the network's performance. The FALCON ALT assessment framework was developed to:

- Model the technique trial sections of network, to allow the performance of the pre-existing NOPs to be examined;
- Identify alternative NOPs, intended to improve performance; and
- Test alternative NOP locations on the network, and through the use of modelling, assess and validate the benefits of the alternative NOPs with respect to the pre-existing NOPs.

A representation of the framework is shown in Figure 5.

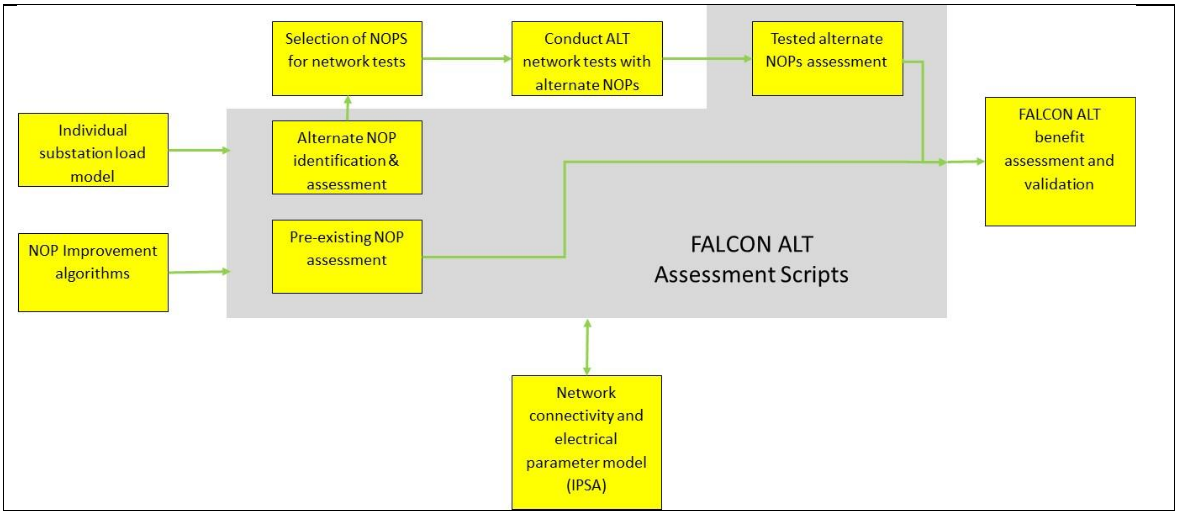

Figure 5: Representation of FALCON ALT assessment framework

4.2 Overview of load flow modelling

Modelling and validation activities involved;

- Establishment of TNEI IPSA models of the base network;
- Conditioning of load models for substations on the network (with capability to scale to measured feeder currents);
- Development and use of Python scripts to: automatically apply the appropriate (time varying) substation load; calculate and adjust the position of the normally open points as required; and generate and output results files; and
- The modelling and validation was highly dependent on the scripts to handle data input and output from IPSA, control of switch states in the network models, and general control of multiple load flow cases that were generated and examined.

4.2.1 Power flow analysis models

The two representative trial networks were modelled from Milton Keynes area, based on a cable and OHL network. The cable network is fed via two primary 33/11kV substations with a total of seven feeders from Newport Pagnell and Marlborough Street substations. The network includes 137 buses and 143 branches (see Figure 6).

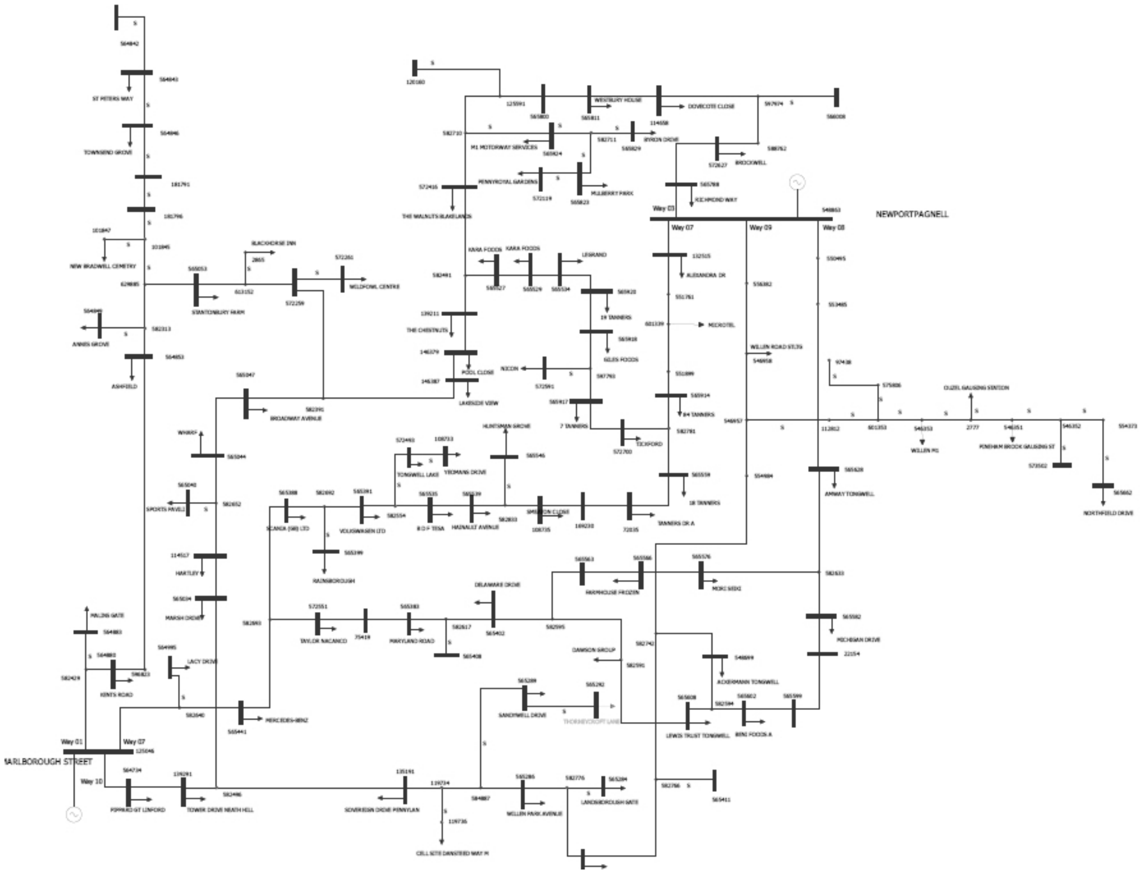

Figure 6: IPSA model for the Newport Pagnell and Marlborough Street substations

The OHL network is fed via two primary 33/11kV substations with a total of five feeders from Newton Road and Winslow substations. The network includes 266 buses and 269 branches and a distributed generator.

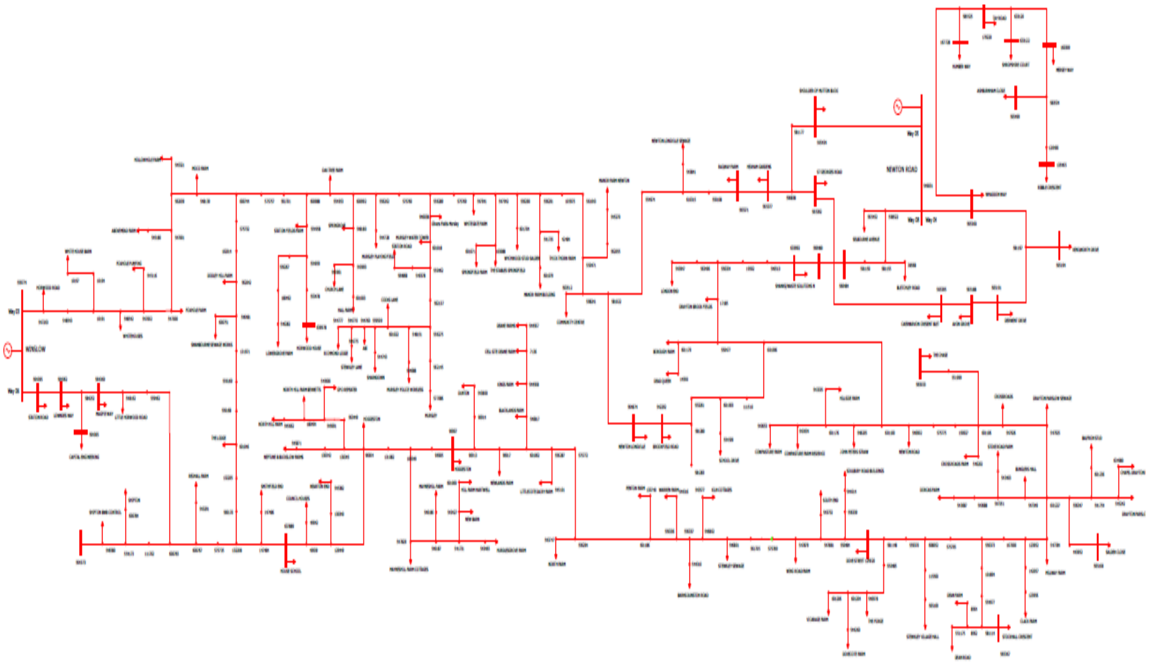

Figure 7: IPSA model for the Newport Pagnell and Marlborough Street substations

WPD provided connectivity and electrical parameter data and the networks were also cross checked against other WPD provided data sources.

The voltage at the primary substations was assumed to be 11.3kV, typical of Primary substation voltages.

LP 5.	Up-to-date models of the system with all required information were not easily available. Additional time was spent cross checking multiple sources against old data were required. This needs to be properly factored into future work.

4.2.2 Substation load models

The WPD provided estimated distribution substations load profiles (from a WPD modelling approach that develops models of loads at each individual substation) were used in the modelling. The load profiles at each 11kV substation gave values for 48 half-hourly periods of each day of a year. The results of the load modelling were cross checked against measured static indicators including maximum demand indicators and the winter max at each substation. The modelled substations were then aggregated according to their normally connected feeder. When necessary, the individual substation loads were then uniformly scaled according to measured feeder load. The power factor at each substation was assumed to be 0.95 as is typical in distribution system modelling.

Customer numbers were identified from reports to OFGEM on customer interruptions and compared to the last MPAN count.

LP 6.	Key data and analysis requirements for off-line or on-line/real -time assessment of optimal position of NOPs have been established. This forms the basis for a template for future work in this area

LP 7.	Network modelling is a pre-requisite for looking at ALT NOP locations

4.3 Alternate NOP identification approaches

There are many published methods for optimising a Network. However, with a network of this size and complexity and to ensure expandability, heuristic approaches were taken. Two different objectives were chosen to look at different methods for determining the open points. The first method (referred to as method 1) looked to minimise losses while the second method (referred to as method 2) looked at increasing headroom capacity as measured at the first branch out of the primary.

4.3.1 Overview of losses minimising algorithm

Detailed investigations were carried out to establish the preferred method of determining network configuration based on minimising losses. This resulted in the preferred method described below.

The method works by meshing the modelled network and carrying out a single load flow analysis, for a given time period and its associated substation loads, from which a set of minimum (independent) voltages around the network were determined. These independent voltage minimum points translate to a set of normally open points (NOPs) associated with the specified time period/set of substation loads that are used to change from a mesh configuration to an open feeder arrangement.

As a point of detail, the NOP associated with an identified independent voltage minimum point is established as the branch connected to the voltage minimum point with the lowest power flow. Once the correct numbers of NOPs have been identified (so there are no meshes within the network) these become the basis for the new ALT configuration.

It should be noted that this approach can flag additional voltage minimum points. This occurs if the load flow analysis identifies two or more points in the network next to each other where the voltage is equally low. This shows a small area of uncertainty as to where the preferred NOP position might be, and this manifests itself as a choice of multiple normally open points around the same location.

LP 8.	It is not always clear where a NOP should be located from the model and the choice of a number of closely clustered alternatives may exist. These typical straddle small loads and therefore the choice of location in this instance is dependent on other factors such as “convenience” within these clusters.

Development of this approach highlighted the following:

LP 9.	Modelling the changes in NOP location shows that a trade-off exists between key benefits of improving losses, equalising customer numbers and increasing capacity headroom.

LP 10.	It is time consuming to determine NOP's using many load flow solutions on such large Networks. Therefore fixed points (peak load and minimum load were initially used).

LP 11.	The methodology chosen was based on analysis at peak and minimum load conditions as being indicative of extreme loading conditions. As the results are consistent between the two extremes this suggests that seasonal/daily/weekly load variation using this chosen methodology is appropriate.

LP 12.	It is not possible to directly compare different network configurations as these cannot occur simultaneously and the load is not controllable. A new method of validation of modelling results was necessarily developed.

LP 13.	The accuracy of load distribution is dependent on feeder current measurement as well as estimated load profile. Therefore inaccurate feeder measurement at low values does impact accuracy.

4.3.2 Overview of feeder balancing algorithm

The percentage utilisation of each feeder, as it leaves the primary substation, is used as a measure of how heavily loaded a feeder is (and therefore how much spare capacity remains) because;

- The lines out of the primary substations do not all have the same rating and therefore absolute values are not practical.
- Conventional network design included tapered (varying 11kV main capacity) circuits, however in most cases the most heavily loaded branch is the one straight out of the substation. This may be different if large amounts of DG were present internal to a Network.
- Ultimately to apply this method in practice would result in the need for load measurements around the circuit and the most practical location for these are at the primary substation on each feeder which ties up with the lines being monitored.

As with every multi-variable non-linear optimisation problem it is not possible to improve benefits in all areas at once. So the main focus of this approach is to:

- Identify the extent to which feeders to a portion of network are unbalanced with their pre-existing open points;
- Establish and implement an approach to identify alternative open points that improve the balance of feeders to a portion of network;
- To analyse the benefits and impacts of the potential changes; and
- To propose a set of open points for trials and validate the results.

The process is further complicated if generation exists on the Network. In this case, where the generation is such that its value is significant enough that the feeder is exporting rather than importing (e.g. Figure 8 ci and cii), then the process of using this generation to meet the load along the feeder as far as possible will act to reduce the load at both feeders. However, because of the tapered nature of the Network, it is possible that a line internal to the Network approaches its rating much more quickly than the feeder lines at the primary substation. In this case the objective is not to balance the feeder utilisation, but to balance the network utilisation by looking at all the lines within the Network. Where the generation is insignificant (e.g. Figure 8 bi and bii) the movement will be as for a load only circuit.

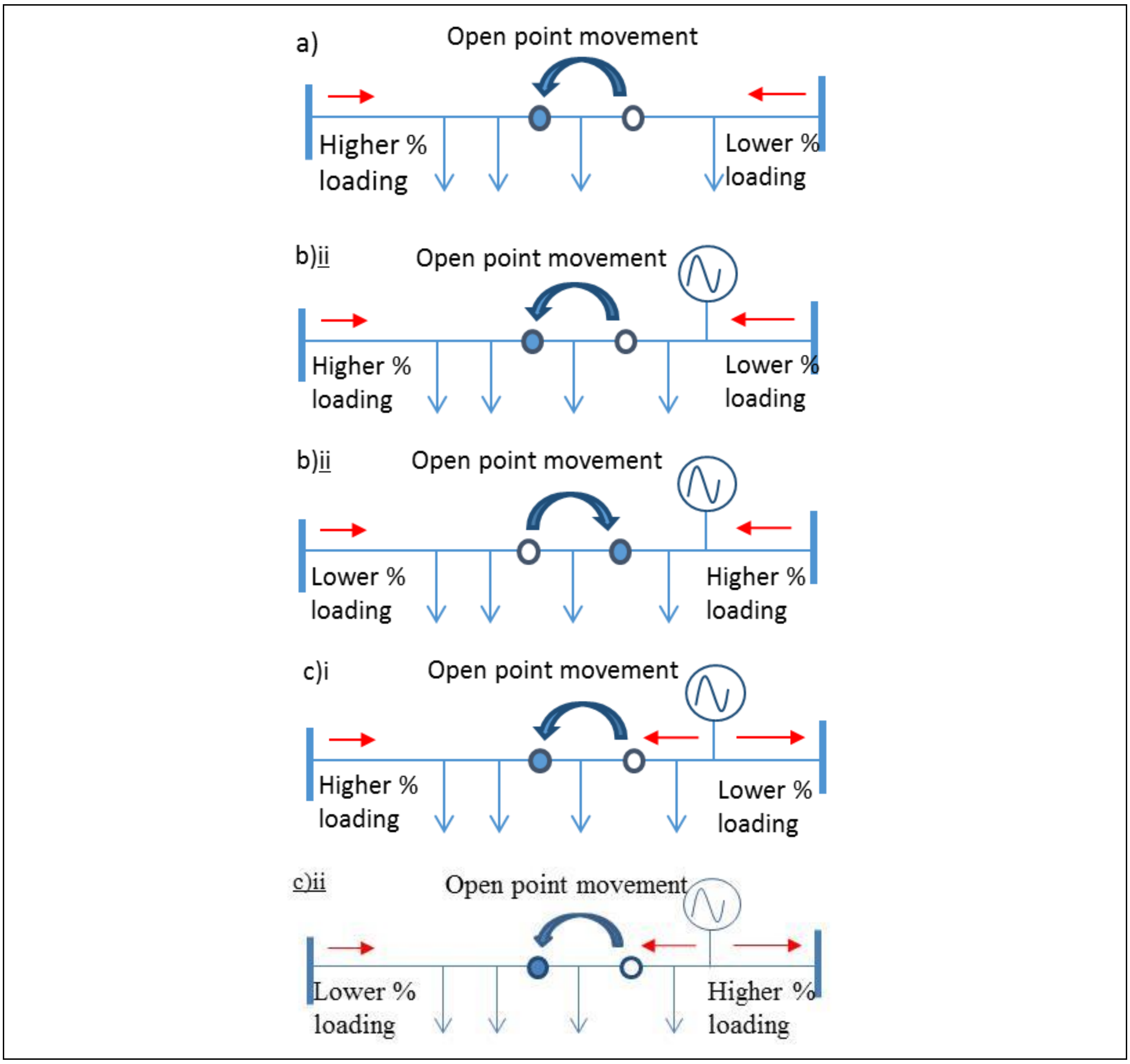

Figure 8 : NOP movement to balance feeder utilisation in the presence of a) load only, b) load and low value generation and c) load and high value generation.

Development of this approach highlighted the following:

LP 14.	Capacity headroom gains cannot occur in every circuit at the same time as this method shifts the available load rather than eliminating it. Therefore although capacity headroom is increased in some circuits, it is reduced in other circuits.

LP 15.	The circuits requiring increased capacity headroom need to be clearly derived in the first instance due to the gain/reduction trade-off. Note: this analysis has been undertaken under normal operational conditions.

LP 16.	NOP location to increase headroom is dependent on distributed generation state. If this is unknown, it is necessary to determine if the generation is predominantly on or off in-order to set the NOP locations.

This approach of examining a portion of network, identifying feeder pairs, improving balance between feeder pairs and iteratively re-examining the network led to an improvement in balance between feeder pairs. This aspect of the methodology recognised that for a section of network with three feeders and two open points, three feeder pairs existed, and that changes to each feeder pair were not independent. The iteration of improving feeder balance for each feeder pair continued until no further improvement by NOP relocation was possible.

It was also recognised that any move of open points may have an adverse impact on voltages, losses and customer numbers (increasing the risk of more customers being affected in the event of a fault). Achieving an improvement in the balance/parity of feeder currents may make the voltages and losses worse and produce undesirable disparity in numbers of customers per feeder. To guard against this, the benefits analysis into voltage and losses is also undertaken using python scripting in conjunction with a commercial load flow software package IPSA.

4.4 Investigation of variation of preferred NOPs across the year

Because the developed analysis approach used a load model bespoke to each individual substation (reflecting reality), it was necessary to consider how this variation impacted on preferred NOP positions as load varied over time. Two points emerged:

LP 17.	Feeder load varies with time at different locations so the optimum location of the NOP may change over time.

LP 18.	The data associated with a year-long switching calendar was considered and regarded as likely to be unmanageable for identifying trends. As a result it was decided that sample days should be chosen, and that these should reflect seasonal/weekly variation and look over the course of a day. This allowed the time varying NOP locations (as per LP17) to be assessed.

Based upon this, the developed modelling framework was used with each of the 48 half-hour periods of 10 representative days from a year to investigate the extent to which preferred open points varied as the substation loads changed across a year.

The representative days covered the five profile seasons (winter, spring, summer, High Summer and autumn), with each season having a Wednesday during the period (representing weekday load) and a Sunday (representing weekend load)

Sample days are shown in Table 1.

Season	Date	Day
Winter	20th Jan 2013	Sun
Winter	23rd Jan 2013	Wed
Spring	21st Apr 2013	Sun
Spring	24th Apr 2013	Wed
Summer	30th Jun 2013	Sun
Summer	3rd Jul 2013	Wed
High Summer	11th Aug 2013	Sun
High Summer	14th Aug 2013	Wed
Autumn	13th Oct 2013	Sun
Autumn	16th Oct 2013	Wed

Table 1:Sample analysis days

Sample output showing NOP location from the load flow analysis over the course of a day was output to excel and showed where the normally open point should optimally be located for each instant in time. If it was not practically possible for a normally open point to exist where identified – then the most appropriate open point was substituted.

The pattern of NOP's can be represented diagrammatically where the stars represent the pre-existing NOPs and the substations are shown by with the location of the open point at an RMU identified with reference to the primary feeder they are connected to.

busbar	565391	582554	565535	565535	565539	565539	582833
branch	582554	565535	582554	565539	565535	582833	565539
	Volkswagon (41D5193)-(NP side)	Volkswagon (41D5193)-(NP side)	B D F Tesa (41D5676)-MS side	B D F Tesa (41D5676)-NP side	Hainault Av (41D5390)-MS side	Hainault Av (41D5390)-NP side	Hainault Av (41D5390)-NP side
00:30						582833	
01:00						582833	
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Figure 9: Preferred open points for a Winter Sunday on the Cable Network around Hainault Avenue

4.5 Dependency on load model accuracy

The losses minimising analysis approach was also used to test the dependency of the modelling framework on the load model assumptions. To do this, two different analyses were complete identifying preferred NOPs and compared:

- An analysis of representative 24 hour periods using estimated substation load profiles (scaled according to actual feeder currents for that period); and
- An analysis for the same period using a Monte Carlo approach where a large number of random distributions of substation load that summed to the same actual feeder currents.

LP 19.	Randomly distributing loads over a large number of load flow iterations allows the impact of load uncertainty to be assessed by generating probability functions of the location of the normally open points based on no prior knowledge of the load distribution.

LP 20.	Monte-Carlo analysis showed good agreement at peak load to the preferred NOPs according to the losses minimising approach. This indicates that load distribution estimate determined NOPs were credible.

SECTION 5

Identified Alternative NOPs

This section outlines the identified NOPs that resulted from analysis of the two separate sections of network (underground and overhead), using the two distinct algorithms identified in Section 4. As a result, the following four assessment exercises were undertaken:

- Method 1 assessment on underground trial network
- Method 1 assessment on overhead trial network
- Method 2 assessment on overhead trial network
- Method 2 assessment on underground trial network

The following sub-sections (Section 5.1 to Section 5.3) provide context to the assessment, and outline the identified preferred NOPs that resulted from the analysis.

5.1 Method 1 Assessment of Underground Trial Network

This assessment was initially made at an early stage in the technique trial. Two sets of NOP positions were identified, and subsequently tested. The analysis was based on one week of load data for the summer period (when the network tests were expected to take place). This early analysis identified static NOP positions (i.e. positions that were a fixed best fit through each hour of the day, and across days of the week). Subsequent analysis considered variations in NOP positions across hours in the day, days of the week, and seasons of the year, through modelling using 10 representative days (as discussed in Section 5.1.5).

5.1.1 Initial test configuration

An initial test configuration was identified and implemented as the first ALT test to prove both FALCON project assessment processes, and data gathering processes. This configuration is shown as a stylised diagram in Figure 10.

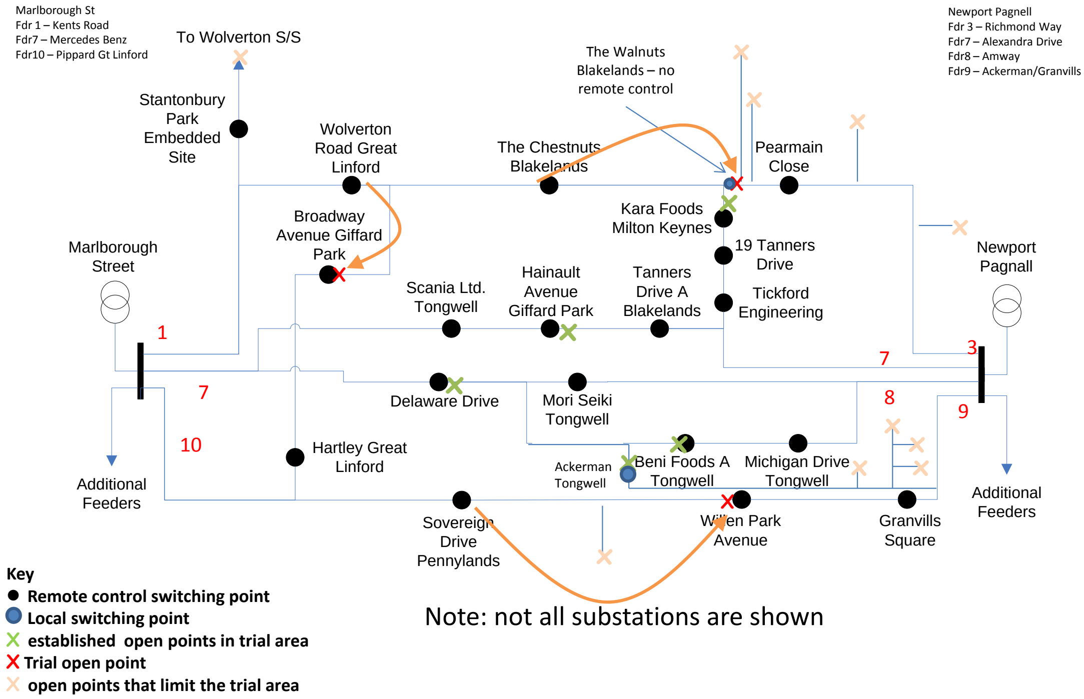


Figure 10 : Stylised network diagram showing changes for 22-29 May – initial test configuration

Results from this trial were used to initially establish the benefit assessment, and results are not presented in this report.

5.1.2 (Preferred) Configuration 1

A preferred configuration was also developed. Ideally this would have included the movement of all eight NOPs. For reasons of practicality in this early phase of trials, seven NOPs were actually moved as a trial.

The preferred configuration is shown in Figure 11.

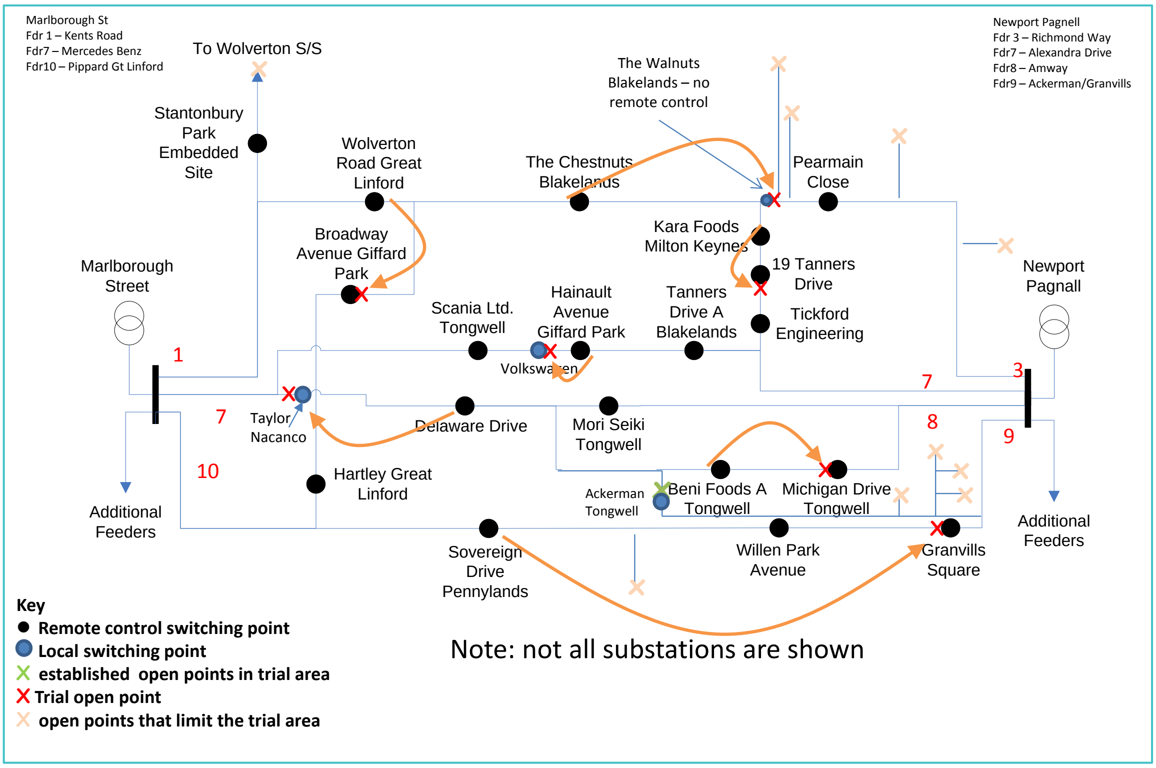


Figure 11: Stylised network diagram showing changes for 17-24 Jun - Configuration 1

5.1.3 (Ideal) Configuration 2

A further configuration was also developed (after implementation plans had been set) and was used in benefit calculations by way of comparison. This configuration was referred to as "ideal" in the context of progress at that stage of the trial. This configuration was not implemented as switching points were not available at all these "ideal" points identified through modelling, but calculated results were prepared and are shown in this report.

The "ideal" configuration (2) is shown in Figure 12.

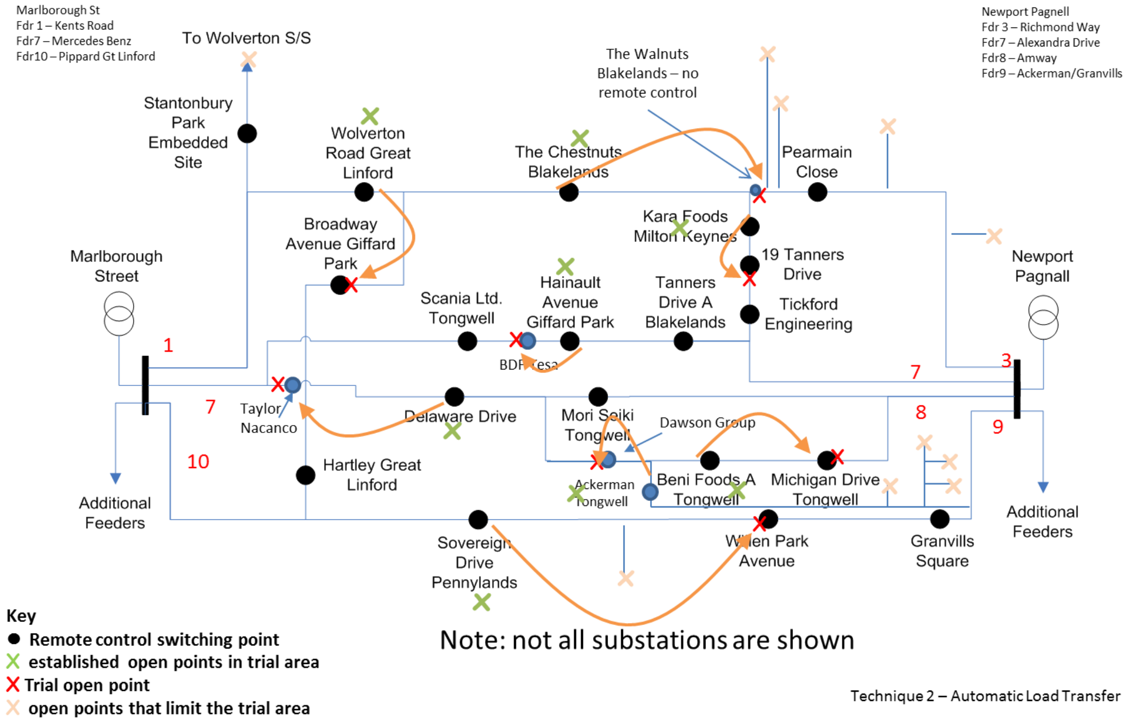


Figure 12: Stylised network diagram showing changes for 17-24 Jun - Configuration 2

5.1.4 Technique trial test programme

Up until the end of June 2014, three configurations were used within the trial operation: the pre-existing configuration; the initial test configuration and the practicable preferred configuration. The time periods for data capture are given in Table 2.

Trial periods	NOP configuration
15th -20th May 2014	Pre-existing NOP configuration (Figure 1)
23rd -28th May 2014	Initial test Configuration (Figure 10)
17th -24th June 2014	Practicable Preferred Configuration 1 (Figure 11)

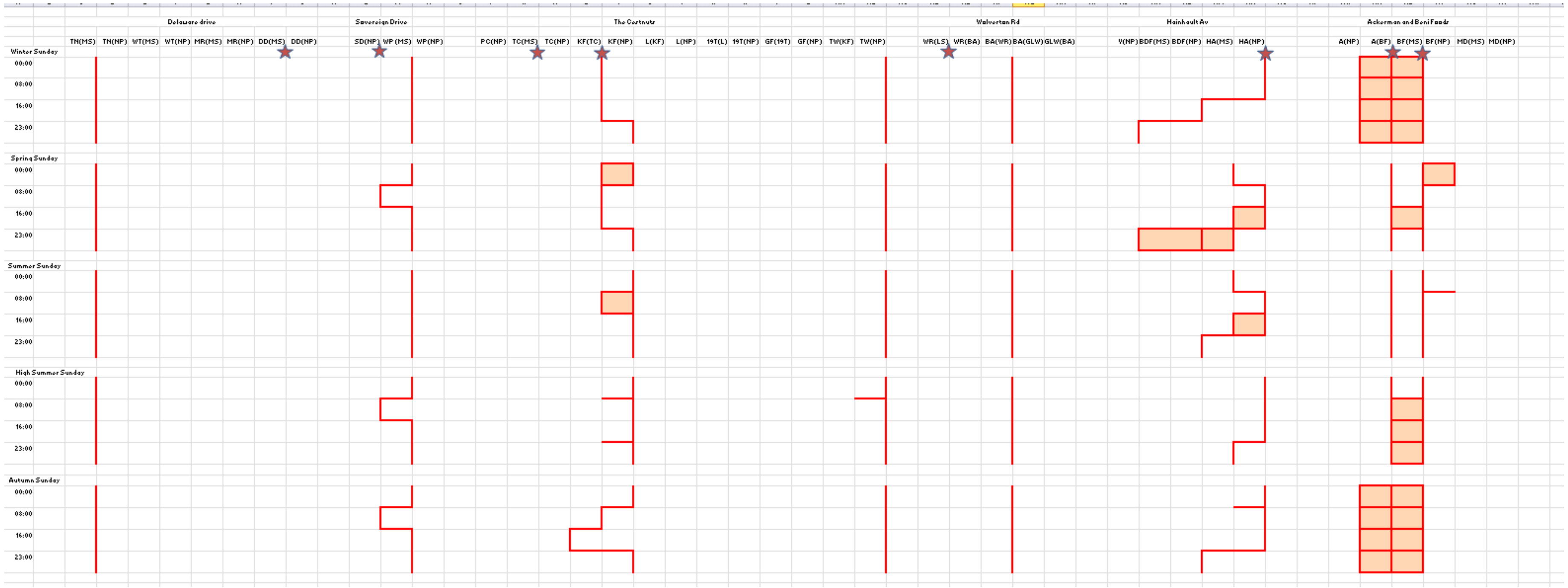
Table 2: Trial periods and corresponding actual NOP configuration

The results of these tests are described in Section 6.

5.1.5 Modelling of variation of NOP positions across the year

Assessment of the variation in NOPs across the year was undertaken by identifying a preferred NOP for each half hour period of ten representative days across the year (one weekday and one weekend day for spring, summer, high summer, autumn and winter)

An example of the graphical representation of the results from this analysis is shown in Figure 13. This shows the results across 24 hours of the five Sundays covering the five profile seasons.



Sunday (winter, spring, summer, high summer, Autumn)

Figure 13: Graphical representation of potential NOP switching pattern for cable

The following recommendations based on the weekday and weekend figures are

- Delaware Drive NOP moves to Taylor Nacanco
- Sovereign Drive NOP moves to Willen Park
- Chestnuts NOP moves to The Walnuts
- Kara Foods – retain Kara Foods, potential for within day movement
- Wolverton Road -moves to Broadway Avenue
- Hainault Avenue - retain Hainault Avenue NOP, potential for within day movement
- Ackerman (closely related to Beni Foods) - retained at Ackerman, with no in-day variation.
- Beni Foods (closely related to Ackerman) - Beni Foods should be retained, potential for within day movement to Michigan Drive.

The movement of the normally open points is very specific to loads. With the accuracy of the load being estimated – these results only indicate where changes could happen based on the estimates of load profile. Future, more accurate monitoring analysis could be undertaken at Kara Foods, Hainault and Beni Foods to determine more accurately the benefit of regular switching.

5.2 Method 1 Assessment of Overhead Trial Network

As for method one assessment of the underground network section, this analysis was also completed at a relatively early stage in the overhead trial and focused on identification of static NOP positions (i.e. positions that where a fixed best fit though each hour of the day, and across days of the week). Analysis of variations in NOP positions across hours in the day, days of the week, and seasons of the year, through modelling using ten representative days was subsequently completed and is presented in section 5.2.4.

5.2.1 Ideal NOP positions

Initial analysis of the overhead section of trial network identified a number of ideal NOP positions that were not practically implementable (i.e. there was no switching device at the identified locations). The result of this analysis is presented in Figure 14.

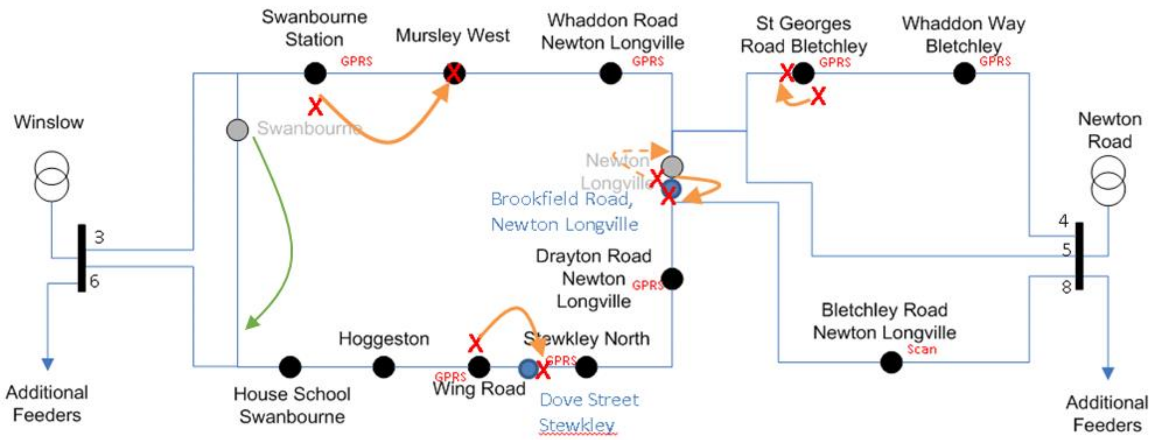


Figure 14: Ideal preferred configuration

5.2.2 Preferred NOP positions

Further analysis constrained to practicable switching points identified a practicable preferred set of NOPs. This is presented in Figure 15.

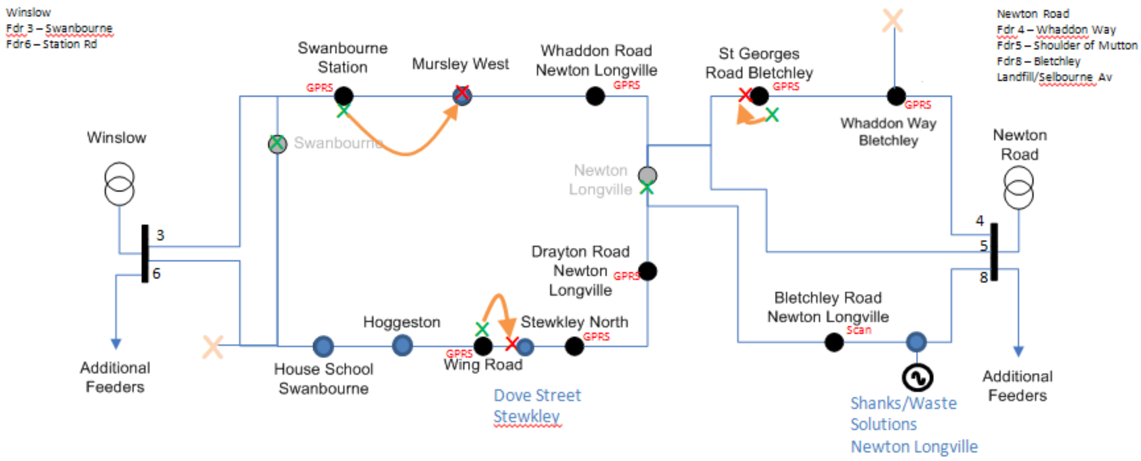


Figure 15: Practical preferred configuration

5.2.3 Technique trial test programme

From 1st October to 13th October 2014, two configurations were used within the ALT OH trial operation: the pre-existing configuration and the practicable preferred configuration. The time periods for data capture are given in Table 3.

Trial periods	NOP configuration
1st -6th October 2014	Pre-existing NOP configuration (Figure 2)
8th -13th October 2014	Practical preferred configuration 1 (Figure 15)

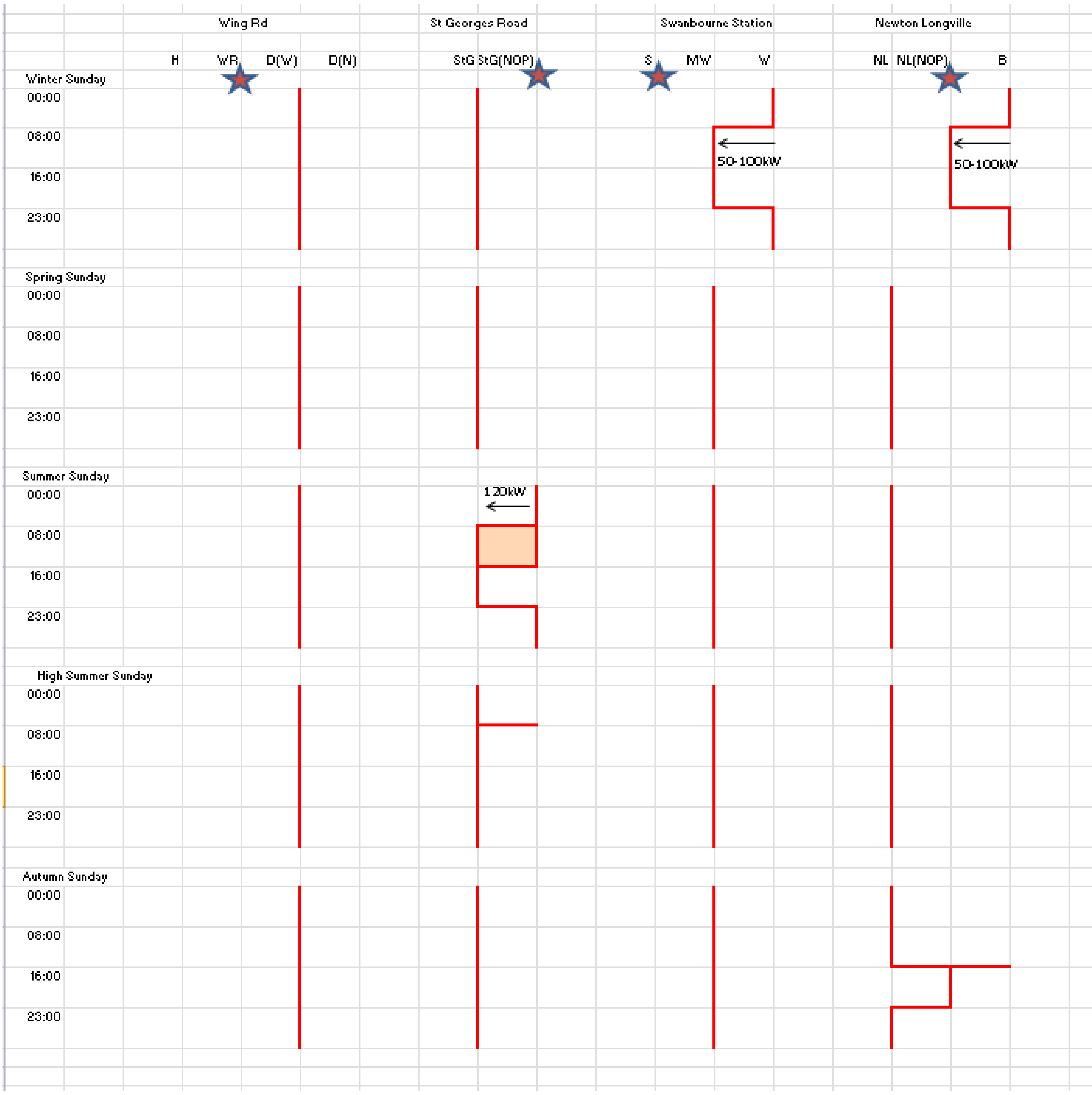
Table 3: Trial periods and corresponding actual NOP configuration

The results of these tests are described in Section 6.

5.2.4 Modelling of variation of NOP positions across the year

Assessment of the variation in NOPs across the year was undertaken by identifying a preferred NOP for each half hour period of ten representative days across the year (one weekday and one weekend day for spring, summer, high summer, autumn and winter).

An example of the graphical representation of the results from this analysis is shown in Figure 16. This shows the results across 24 hours of the five Sundays covering the five profile seasons. It should be noted that the pre-existing Swanbourne NOP location has no practicable adjacent switching points (as identified in initial analysis Section 5.2.1), remains in its pre-existing position, and is not shown in the graphic. In addition, full load at the significant generation site was assumed (this is reasonable based on examined load profiles).



Sunday (winter, spring, summer, high summer, Autumn)

Figure 16: Graphical representation of potential NOP switching pattern with full generation

From Figure 16 it can be seen that the modelling identifies no variation in the preferred NOP position of the pre-existing Wing Road NOP, and negligible change in the St Georges Road pre-existing NOP. The changes in load for the Swanbourne and Newton Road pre-existing NOPs are also small (50-100kW), occurring as seasonal load increases. Similar results were found for weekdays (see Appendix D); and based on this, no substantive grounds were found to take forward higher frequency switching (i.e. varying with hours of the day, days of the week and weeks in the year) using this method of NOP identification.

5.3 Method 2 Assessment of Overhead Trial Network

5.3.1 Potential NOP positions

Figure 17 shows a high level view of the current feeder capacity usage on each feeder as an approximate percentage of feeder rating. Winslow Way 03 has a very low current and the measurement at this level is below the accuracy of the transducer. To balance the feeder currents there is scope, for example, to move the load from Newton Rd Way 05 to Winslow Way 03. There is also 5MW of generation on Newton Rd Way 08 close to the primary which impacts the analysis on this feeder.

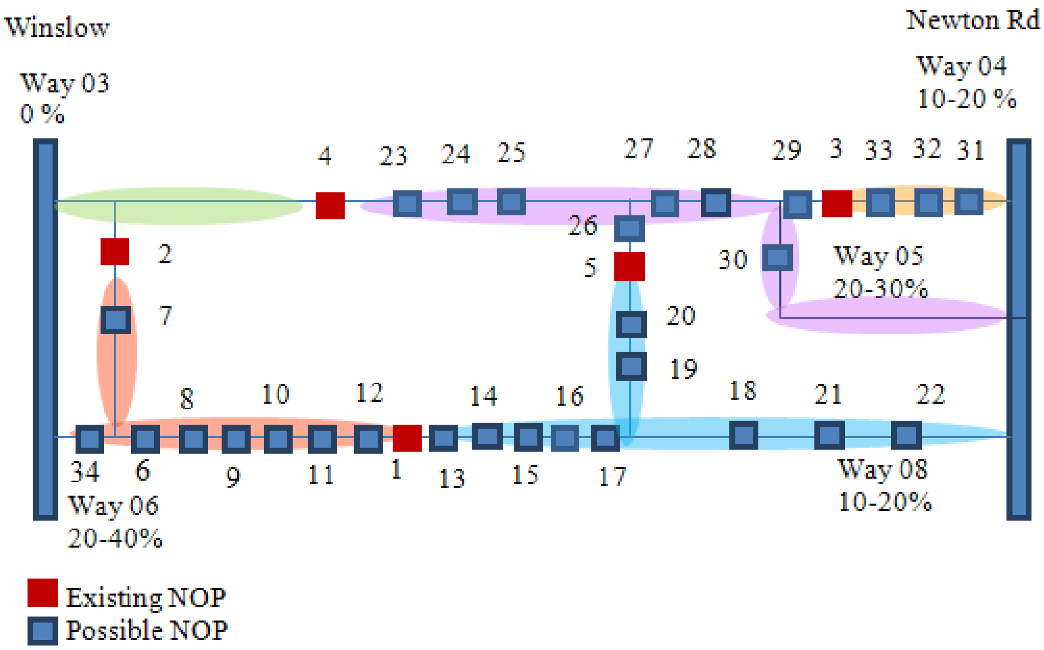


Figure 17 : Possible Open Point locations on OHL trial network using Method 2 analysis

Referring to Figure 17, the following observations can be made based on the location of the possible switching points on the Network;

- There is no feasible alternative for the Swanbourne NOP (2) as open point 7 is not in practice a switching point, so this needs to remain as is.
- Winslow Way 06 and Newton Road Way 05 are the heaviest loaded and therefore moving load away from these feeders will help to balance the loading.
- There are two options for moving the load away from Newton Rd Way 05:
  - The NOP at St Georges (3) could be moved to the other side of the existing NOP (from position 3 to 29). Unfortunately there is no scope to move it further from Newton Rd Way 04 (toward 28) because a mesh would then exist between Newton Rd Way 04 and 05. Moving this NOP to Newton Rd 05 (30) results in a low utilisation of Newton Rd Way 05 and therefore this is not considered a practical option.

- Transferring more load to Newton Rd Way 08. This can be achieved by moving load from Newton Longville (5) to the other side of the substation (to 26)

- Winslow Way 06 has the highest feeder utilisation (due to a low rated line from the substation). To reduce the loading on this, it is desirable to move the NOP from Wing Road (1) towards Winslow (potential points 12, 11, 10, 9, 8, and 6)
- The combinations of NOP movement likely to show the highest impact are Wing Road and Swanbourne Station and concern load changes between Winslow Way 6 and Newton Rd Way 8 and Winslow Way 3 and Newton Road Way 5 respectively.

A summary of potential open point movement is shown in Table 4. This shows one NOP remaining unchanged and two NOPs moving to alternative sides of the substations. A list of the potential open points for the final two NOPs (Wing Road and Swanbourne Station) are also shown.

Existing NOP	Name of existing Open Point	Potential open point moves
1	Wing Road	6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19, 20, 34
2	Swanbourne	Fixed at 2
3	St Georges Road	to 29
4	Swanbourne Station	23, 24, 25, 27, 28, 30
5	Newton Longville	to 26

Table 4: Possible combinations of OHL NOPs

The movement of NOP1 and NOP4 are independent of each other, a fortuitous feature of this network that leads to simplification of subsequent analysis. Where this independence does not exist a more complex iterative procedure must be used looking at all possible feeder pairs and understanding their impact on each other. This means that the NOP positions can be identified separately, rather than needing to consider any one possible position for NOP1 combined with any one possible position for NOP4, giving a total number of possible combinations of 12x6=72. To help with percentage feeder utilisation, NOP1 will move towards Winslow and NOP4 will move towards Newton Road.

The process of identifying the best open point is summarised as follows:

1. Determine the feeder pair with the largest percentage average difference in utilisation over ten days
2. For a feeder with load only
   a. Move the open point from the highest percentage feeder utilised side to the lowest percentage feeder utilised side until the least difference in feeder utilisation exists.
3. For a feeder with load and (significant) generation
   a. Move the open point from the generation network utilised side to the other network utilised side until the smallest difference in network utilisation exists (the

feeders may be unbalanced but this results in the highest network headroom see Figure 8).

4. Repeat process 1-3 for all feeder pairs and until no further network improvement is possible.
5. Determine impact on other parameters for example, losses, bus voltage and customer number division across feeders.

LP 21.	The process for determining the NOP to maximise headroom capacity is both iterative and currently depends on manual intervention because of the subjective nature of determining when Network improvement is no longer possible.

The network between Newton Rd Way 08 and Winslow Way 06 has 5MW of generation near Newton Rd. Under normal operation the generation exports power through Newton Rd to the 33kV Network. So moving the NOP away from Newton Rd towards Winslow not only reduces the import through Winslow, it reduces the export through Newton Rd freeing headroom in both lines. Under this algorithm alone, the location of the NOP point moves very close to Winslow.

LP 22.	Generation impacts NOP location in a much more significant manner when dealing with Network capacity optimisation (compared to minimising network losses) and at high levels of generation this can be significant as shown by the change in location of NOP 1 on the OHL Network.

5.3.2 Investigation of variation in preferred NOP positions across the year

Modelling (that identified preferred NOP positions for each half hour of the 10 representative days) was undertaken, based on the context and process described in Section 5.3.1 above.

Using this algorithm, the open point locations for minimising percentage feeder utilisation can be found. Figure 18 shows an example of the results; the percentage feeder utilisation and open point location between Newton Road Way 05 (NR05) and Winslow Way 03 (WS03) for the 480 plotted points of the 48 half hour periods over the ten typical days.

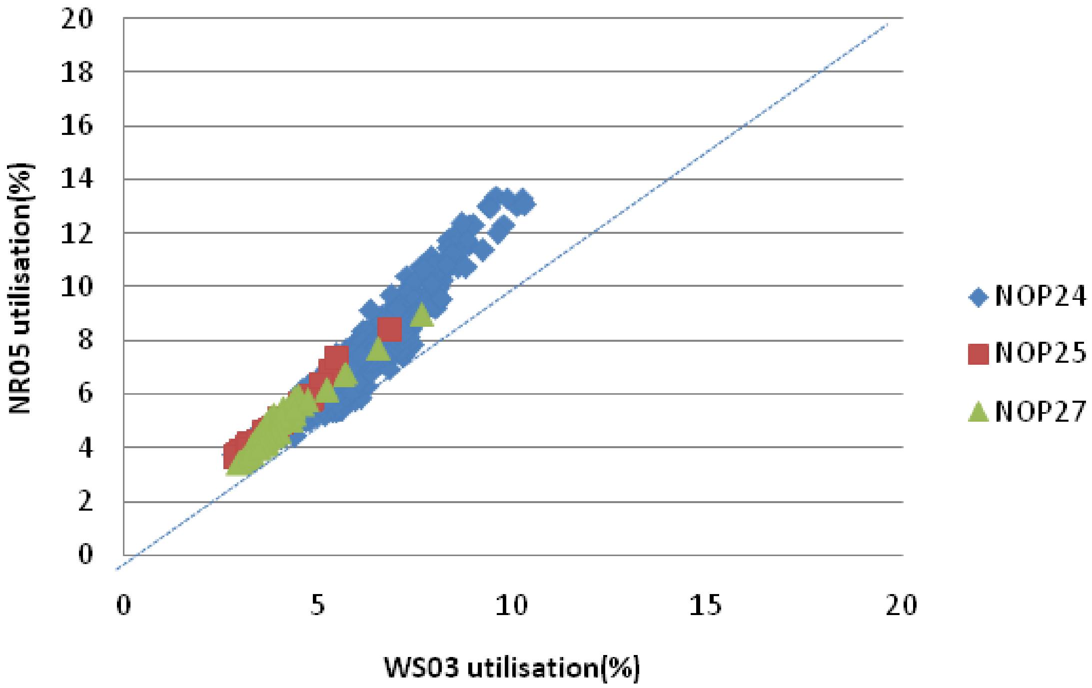


Figure 18 : Percentage Feeder utilisation of NR05 and WS03 over 10 typical days with calculated open point position

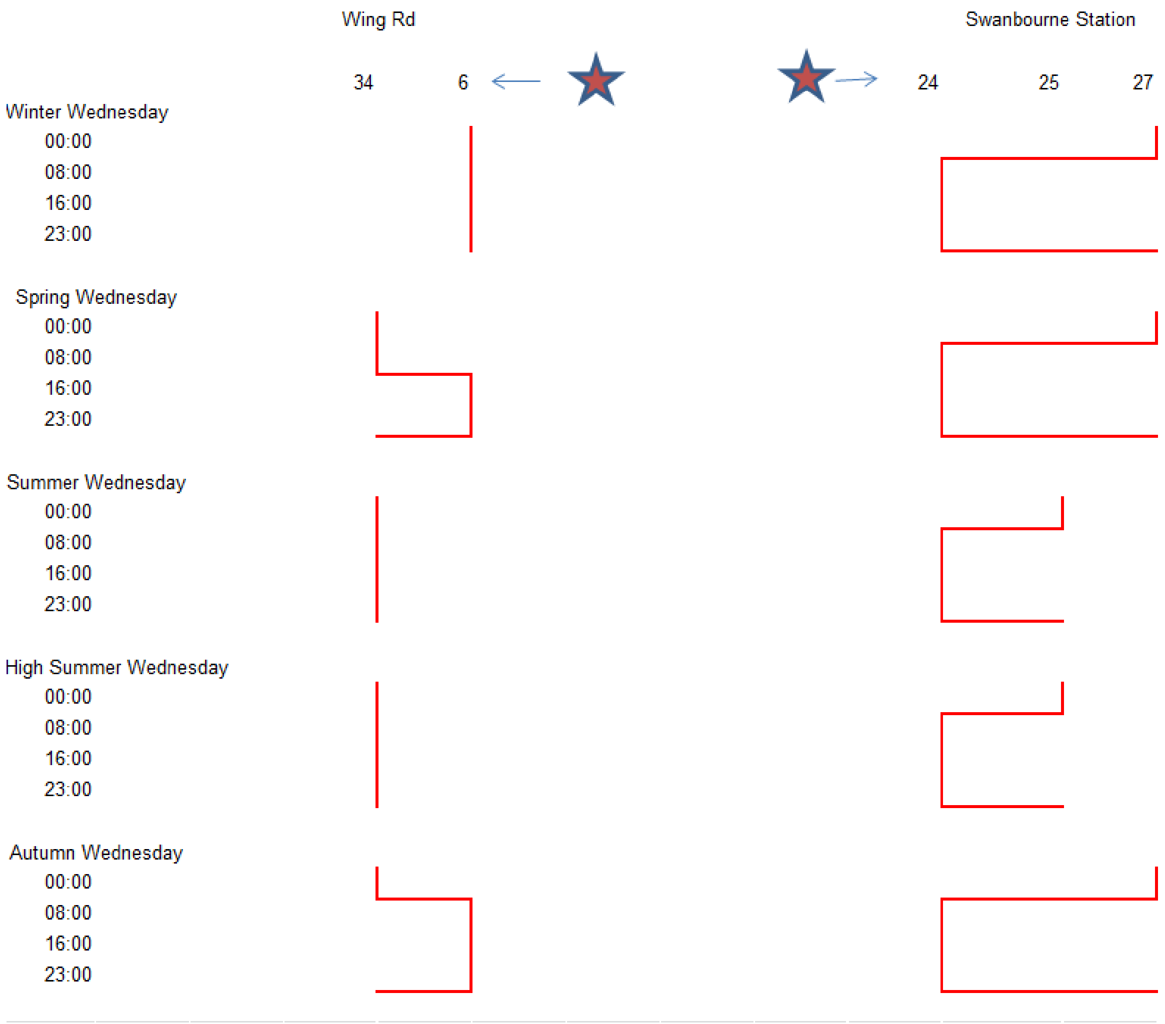
LP 23.	As with other methods of determining NOP location, the NOP shifts with changes in load (and generation) over time.

LP 24.	On both Networks, the NOP typically moves between adjacent or closely located switching points such that the location of possible NOP points is clustered.

Figure 18 shows a very good level of balance between two feeders can be achieved at very low loads (up to approximately 8%). At feeder loads above this, the load becomes slightly biased towards NR05. The deviation away from a "line of balance" indicates the limited capability to adjust load between feeders imposed by the existence of practical switch points with large quantities of load in-between.

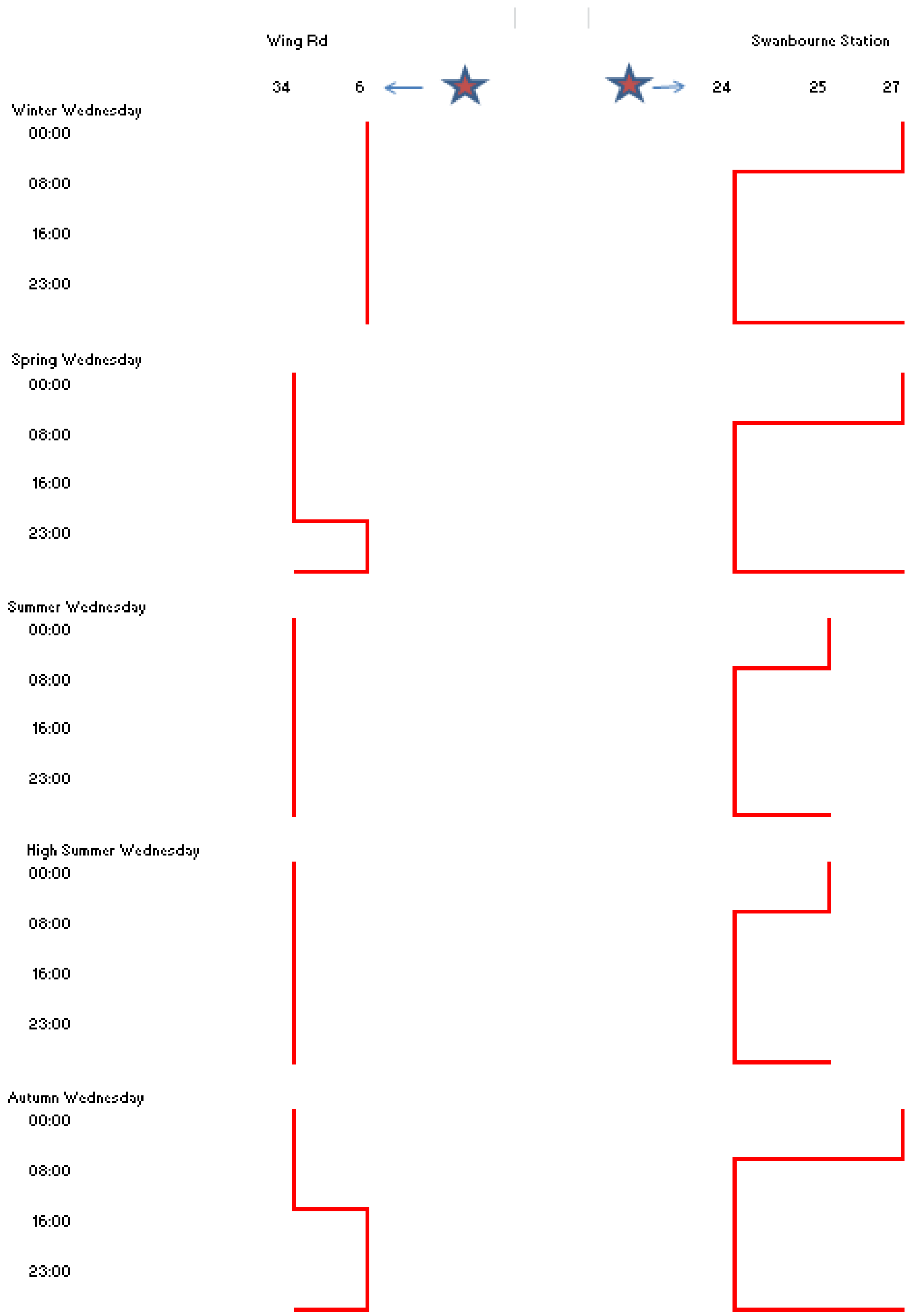
In this example, although there are six possible NOPs between feeder WS03 and NR05, the simulation results show that the algorithm only ever identifies three of them; 24, 25 and 27 to balance feeder utilisation. The most frequent position of normal open point locations were recommended as the optimal configuration for operating under trial conditions.

The calculated switching patterns for these Networks are shown in Figure 19 and Figure 20 for weekends and weekdays. The overhead line network only has two substations which change location at any one time to help balance the feeder utilisation therefore only these two are shown.



Sunday (winter, spring, summer, high summer, autumn)

Figure 19: Graphical representation of potential NOP switching pattern for OHL with full generation



Wednesday (winter, spring, summer, high summer, autumn)

Figure 20: Graphical representation of potential NOP switching pattern for OHL with full generation

Results show that on the overhead line network;

- There are no significant differences between weekdays/weekends
- The NOP at Swanbourne Station has shifted in the same direction as that in optimisation method 1. However the NOP at Wing Rd has shifted in the other

direction from the switching under method 1 because of the presence of the generation aiming to reduce feeder loading.

- The number of switching operations/day is comparable to method 1 and is either none or two.
- Across seasons there is no significant pattern of changes in preferred NOPs. Where there is higher loading in Autumn and Winter small seasonal shifts in normally open point at Swanbourne (24) and Wing Road (34 to 6) could be considered.

5.3.3 Preferred NOP positions

Based on the analysis presented in Section 5.3.2, the configuration shown in Figure 21 was adopted for testing on the network.

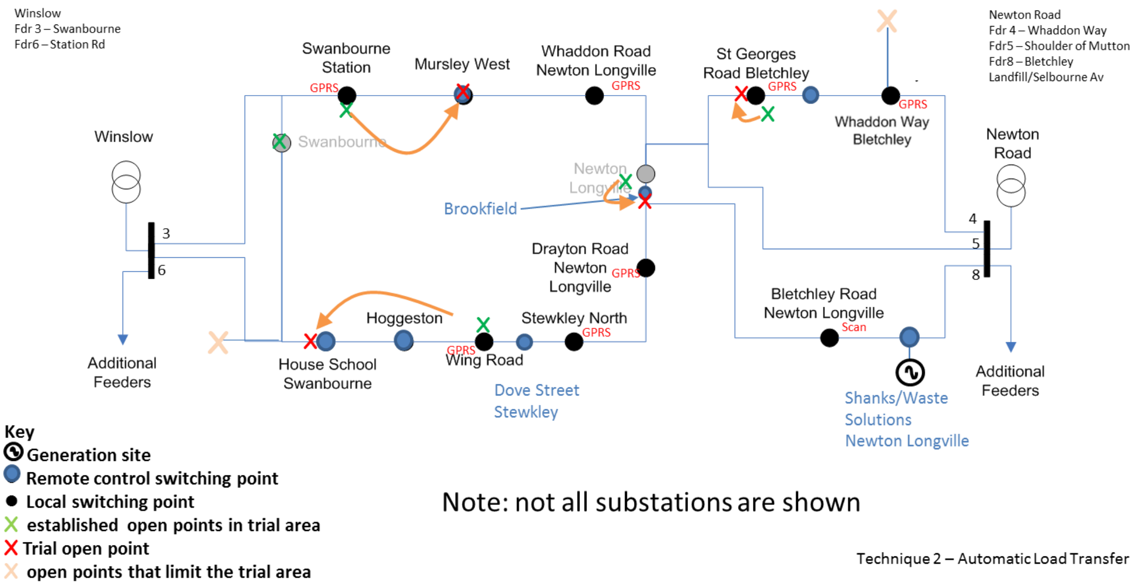


Figure 21: Stylised network diagram showing changes for network test starting 02/06/2015

5.3.4 Technique trial test programme

From 1st to 15th April 2015, two configurations were used within the method 2 ALT underground trial operation: the pre-existing configuration and the preferred configuration. The time periods for data capture are given in Table 5.

Trial periods	NOP configuration
1st -7th April 2015	Pre-existing NOP configuration (Figure 1)
8th – 15th April 2015.	Practical preferred Configuration 1 (Figure 21)

Table 5: Trial periods and corresponding actual NOP configuration

The results of these tests are described in Section 6.

5.4 Method 2 assessment on underground trial network

5.4.1 Potential NOP positions

Within this analysis method, the switchable points are restricted to maintain a fully radial network and avoid the possible impact from other feeders through a junction (point of interconnection between two feeders). The possible points for each NOP are listed in Table 6.

NOP number	Nominal NOP	NOP combination
NOP 1	Delaware	(9, 10, 11)
NOP 2	Sovereign	(12, 13, 14, 15)
NOP 3	Chestnuts	(16, 17, 18)
NOP 4	Kara Foods	(19, 20, 21, 22, 23, 24, 25)
NOP 5	Wolverton Rd	(26, 27, 28, 29, 30, 31, 32, 33)
NOP6	Hainault	(34, 35, 36, 37, 38, 39, 40, 41, 42, 43)
NOP7	Ackerman	(44)
NOP8	Beni Foods	-

Table 6: Possible locations and combination

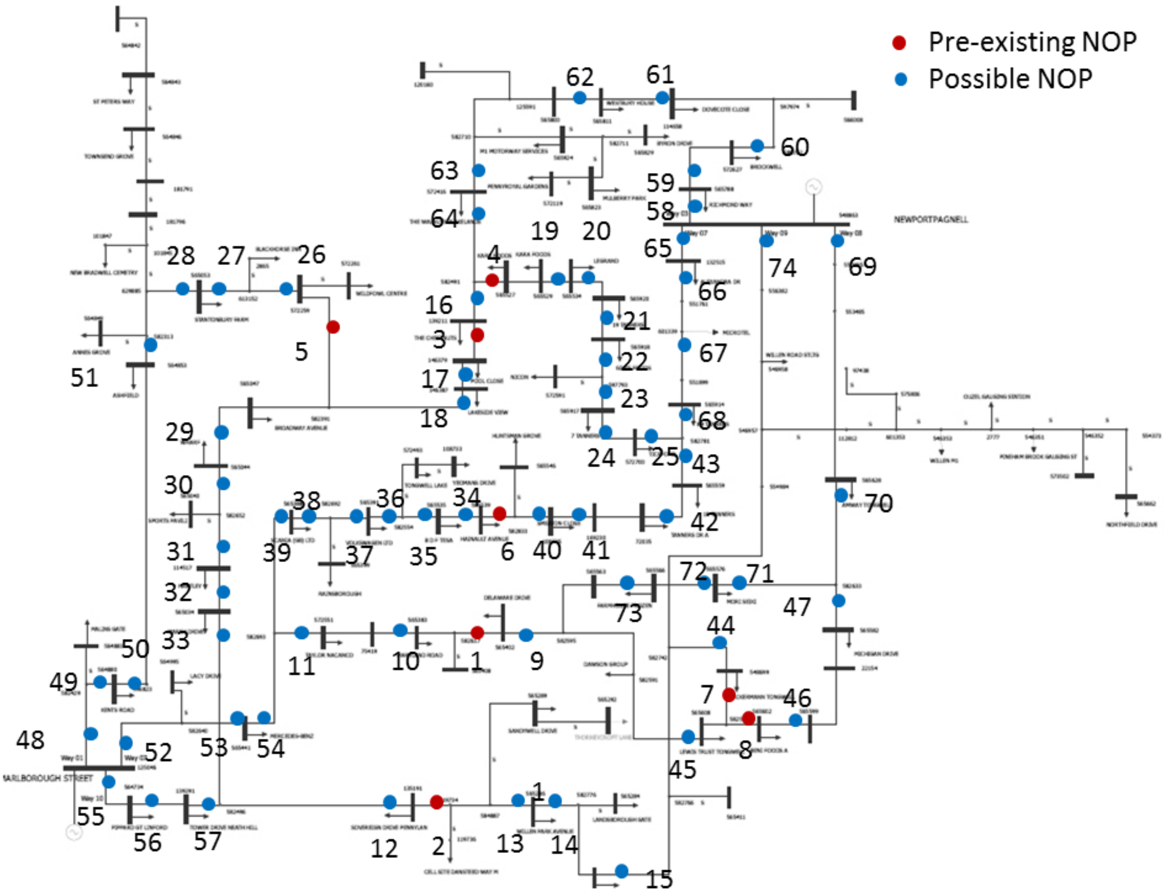


Figure 22: Illustration of possible NOP location for feeder utilisation balance on Cable trial network

5.4.2 Investigation of variation in preferred NOP positions across the year

Modelling was undertaken that identified preferred NOP positions for each half hour of the ten representative days. Results from this analysis are presented in Appendix E. In general it was found that:

- Two of the pre-existing NOPs should remain at their current locations (Beni foods, and Ackerman NOPS);
- Three of the pre-existing NOPs should move to new static locations (Delaware Drive, Sovereign Drive, and Chestnuts NOPs). These locations were resilient to daily, within week, and across seasons variations in load; and
- The remaining three NOPs (around Kara Foods, Wolverton Road, and Hainault Avenue) showed some variation in position as load varied during the day, over the week and across seasons

The potential variation for the nominal Kara Foods, Wolverton Road, and Hainault Avenue NOP positions is shown in Figure 23.

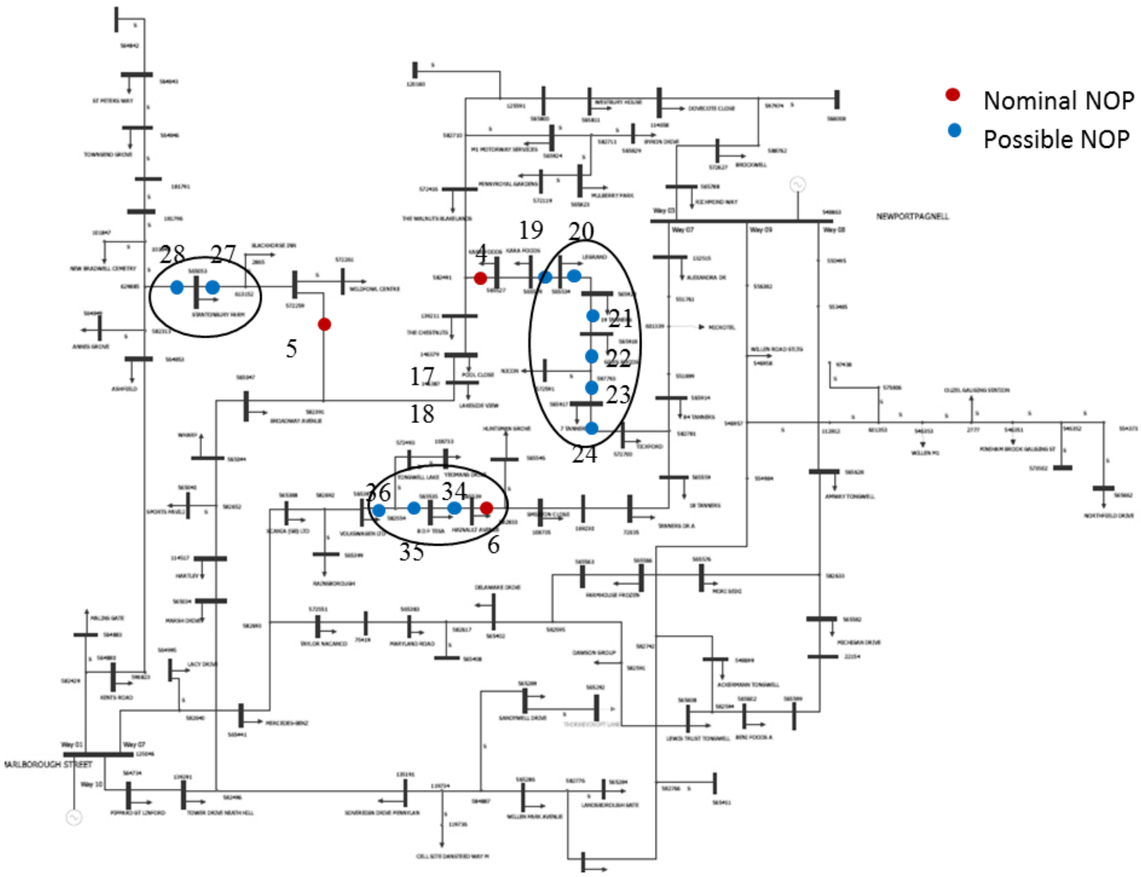


Figure 23: NOP spread points for Kara Food, Wolverton Rd and Hainault

Consideration of the variation shown in Figure 23 suggested that the NOP variation is confined in certain areas and the potential NOPs are quite near to each other. It was concluded that points close to the middle of the variation could effectively be used as a constant trial NOP site as these were identified as being the most frequent locations of the NOP as shown in Appendix N.

This analysis identified the following learning points:

LP 25.	There is more uncertainty on the location of the NOPs within the trial Cable Network as there are more loads closer together. Where there is a confluence of three feeders at a single location the location of the two NOP's associated with this may vary considerably between the three feeders.

LP 26.	A move in optimal location of an NOP is usually triggered across multiple locations at the same time due to the interconnectivity of the Network.

LP 27.	The underground model suggests a greater number of NOP switching operations compared to the OHL Network. However some of these operations involve small changes in load movement from one side of an RMU to the other.

5.4.3 Preferred NOP positions

Based on the analysis presented in Section 5.4.2, the configuration shown in Figure 24 was adopted for testing on the network.

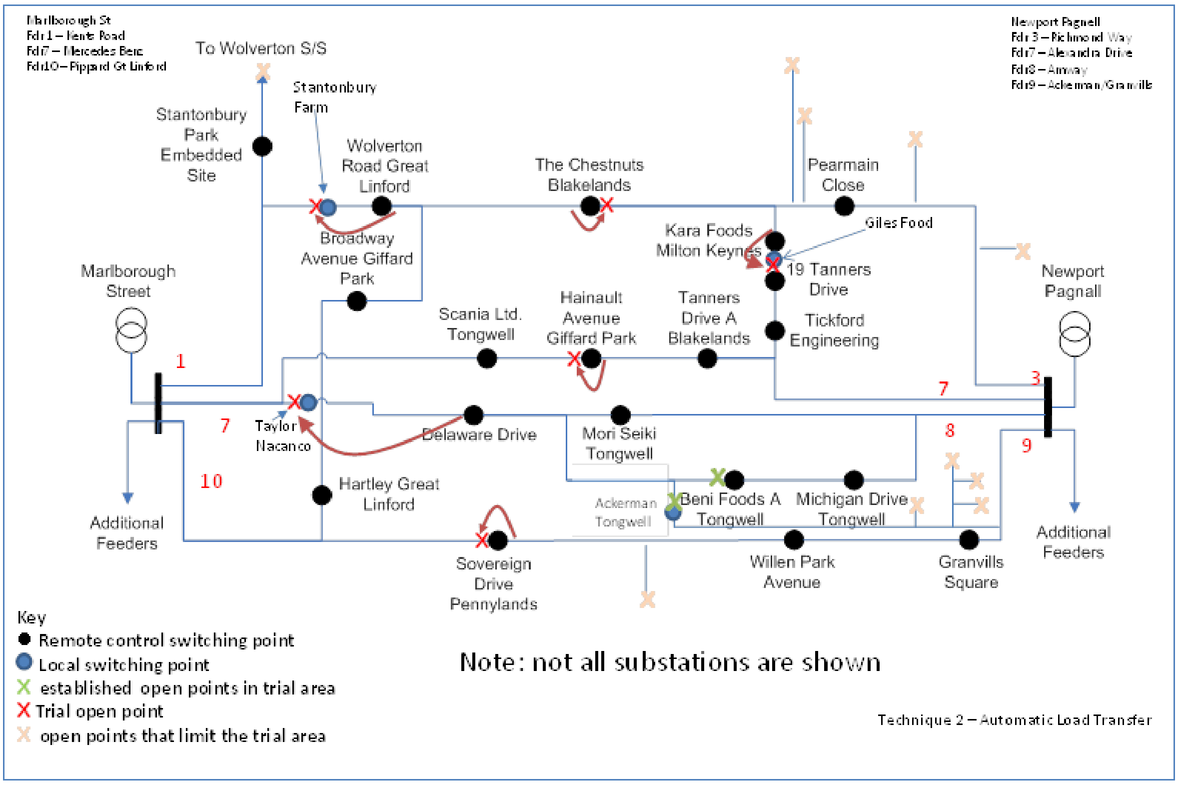


Figure 24: Stylised network diagram showing changes for network test starting 02/06/2015

5.4.4 Technique trial test programme

From 25th May to 16th June 2015, two configurations were used within the method 2 ALT underground trial operation: the pre-existing configuration and the preferred configuration. The time periods for data capture are given in Table 7.

Trial periods	NOP configuration
25th May – 1st June 2015	Pre-existing NOP configuration (Figure 2)
2nd -16th June 2015.	Practical preferred Configuration (Figure 24)

Table 7: Trial periods and corresponding actual NOP configuration

The results of these tests are described in Section 6.

5.5 Generalised learning from the alternate NOP assessment process

LP 28.	The availability of greater analysis at an earlier stage of planning would have altered the choice of ALT switching points. Future practice should allow modelling to inform choice of locations.

- In order to meet Project FALCON time constraints it was essential to order and install additional switchgear and automation devices as soon as possible. Therefore it was necessary to identify suitable substations to install additional remote control prior to being able to carry out an in depth network study or power system analysis.

LP 29.	It is not reasonably practicable to directly measure all improvements that would arise from implementing an alternative NOP configuration over a sustained period of time. Feeder currents may be monitored but monitoring for loss reduction and voltage improvement over the whole network is unlikely to be cost effective.

- The loads will always be marginally different between the two test periods, and inference of improvement in losses and voltage from modelled results is required to inform the basis of our findings.

SECTION 6

Trial Results and Discussion

A significant quantity of results and benefits have been calculated and compared. This chapter is therefore split into a number of sub sections looking at feeder current comparison; modelled trial benefits; time varying switching benefits and a summary.

6.1 Validation

The initial analysis of data collected from the early trials was aimed at validating modelling, and confirming reliance on subsequent benefits analysis.

A key data requirement for modelling of the trial network is quantification of individual substation loads. The individual substation loads cumulatively define the total feeder load, and the individual substation's load characterises the distribution of load along a feeder. Reasonable practicalities dictate that measurement of all loads on non-trivial networks is extremely unlikely, individual substation loads are therefore modelled based on underlying information and assumptions, and (their aggregated time varying feeder load) effectively become a key assumption. This assumption (of distribution of load along a feeder) is important in accurately assessing the losses that exit, but again it is not reasonably practicable to directly measure the losses. Therefore validating the assumptions about distribution of load along feeders is important.

This validation is described in Appendix F.

The conclusion of this validation work is that the measured results and subsequent modelling analysis is satisfactory for outline benefit assessment.

6.2 Feeder current comparison

6.2.1 Method 1: Cable trial network results

The measured and calculated peak feeder currents over each trial week of the cable network trial with open points derived from method 1 are listed in Table 8. Where the measured current is used, a cross check calculated value is listed to ensure total load is correct. The shaded entries show where the current is calculated as opposed to measured. Configuration 2 refers to a set of "ideal" NOP positions (Section 5.1.3).

	Nominal configuration 0		Preferred Configuration 1		Ideal Configuration 2	
	Measured total feeder current (peak)	Calculated total feeder current (peak)	Measured total feeder current (peak)	Calculated total feeder current (peak)	Measured total feeder current (peak)	Calculated total feeder current (peak)
Week 1	633	633	-	632	Not implemented	632
Week 2	-	646	646	646	Not implemented	646

Table 8: Comparison of calculated and measured peak feeder currents during trial periods for cable network

Figure 25 and Figure 26 and the graphs in Appendix P show percentage utilisation of feeder pairs with pre-existing and preferred NOP configurations of Cable network over trial week 1 (15^{th} -20^{th} May 2014) and week 2 (17^{th} -24^{th} June 2014) under the loss minimisation method (method 1).

Figure 25 and Figure 26 are an example showing the change in percentage feeder utilisation between the pre-existing (shown as blue) and preferred configuration (shown in red). Adjusting the open point position allows load to be transferred from Marlborough Street Way 07 (MS07) to Newport Pagnell Way 08 (NP08) with the result that the skew in feeder utilisation (away from line of balanced load between feeders – dashed line) decreases and the percentage utilisation on Marlborough Street Way 07 reduces by around 12% and 8% over week 1 and week 2 respectively. Meanwhile, the utilisation on Newport Pagnell Way 08 increases about 1% and 5% respectively. It is clear that the feeder pair is more balanced with the preferred configuration. The other feeder pairs show a similar set of results and indicate that the differences between measured and calculated feeder currents follow the same trend over consecutive test weeks.

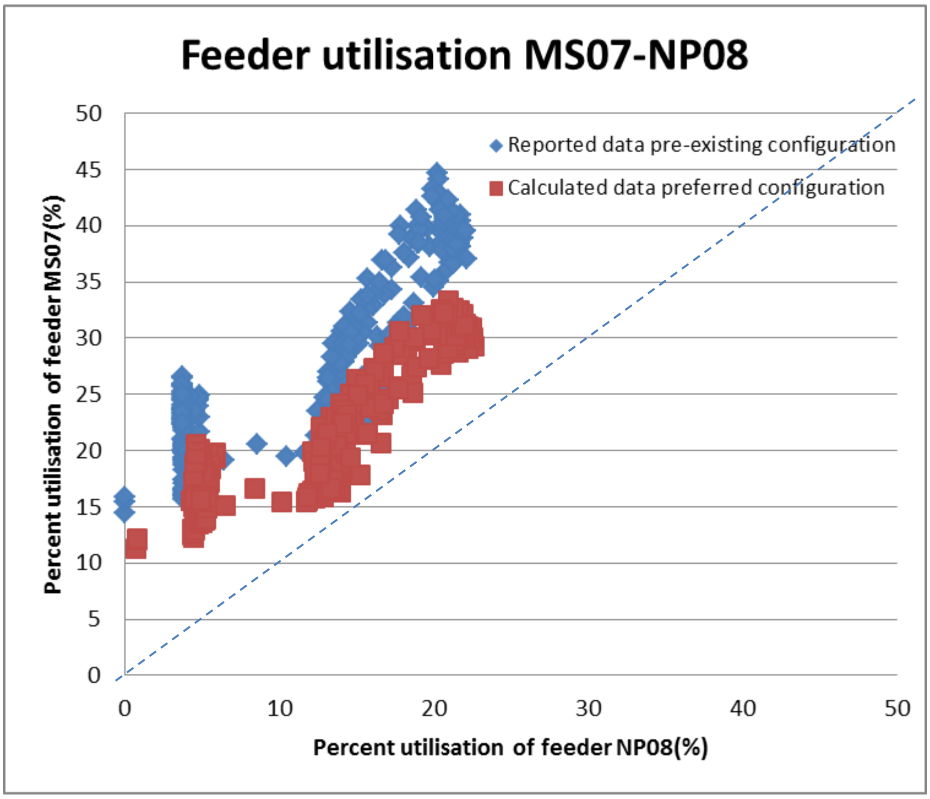


Figure 25: Measured and estimated feeder utilisation of MS07 and NP08 over week 1

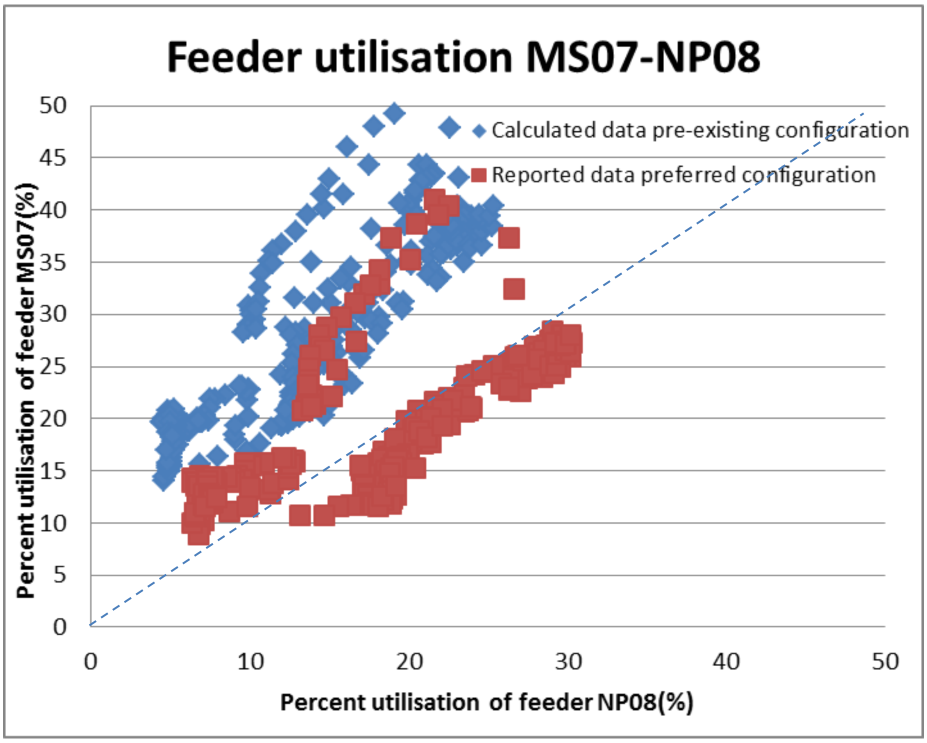


Figure 26: Measured and estimated feeder utilisation of MS07 and NP08 over week 2

Although the balance of feeder utilisation is not one of the objectives of method 1, the improvement on feeder balance can still be seen on certain feeder pairs. Appendix P show that improved balance is achieved on feeder pairs Marlborough Street Way 10/ Marlborough Street Way 01 and Marlborough Street way 07/ Newport Pagnell Way 07.

6.2.2 Method 1: Overhead trial network results

The measured and calculated peak feeder currents over each trial week of the overhead line network trial with open points derived from method 1 are listed in Table 9.

	Nominal configuration 0		Preferred Configuration 1		Ideal Configuration 2	
	Measured total feeder current (peak)	Calculated total feeder current (peak)	Measured total feeder current (peak)	Calculated total feeder current (peak)	Measured total feeder current (peak)	Calculated total feeder current (peak)
Week 1	376	376	-	374	Not implemented	374
Week 2	-	395	393	393	Not implemented	391

Table 9: Comparison of calculated and measured peak feeder currents during trial periods for OHL network

In each trial period, the calculated feeder current varies slightly with the applied NOP configuration because the loss varies (based on the NOP configuration used).

The total load is set to be identical between the modelled configurations while the ratio of the total calculated feeder currents is consistent across the three configurations. If the load distribution or model has been inaccurate then the ratios of calculated total feeder current would have been inconsistent indicating an inaccuracy in load distribution.

The increase in feeder current between the two trial weeks on both the cable and OHL Networks highlights the complexity of this type of analysis because the total load current has increased compared to previous weeks in the trial.

Actual generation at the significant generation site have been used to inform the analysis. The feeder current (only magnitude) does not inform the analysis of direction of power flow. Therefore the feeder current has been notionally signed to show direction of power flow for analysis purposes:

- Assigned as negative feeder current (power exporting through Newton Rd) when the measured feeder current magnitude is smaller than the generation with the difference being equal to the total feeder loads.
- Assigned as positive feeder current (drawing power through Newton Rd) when the measured feeder current is larger than the generation and the total feeder load is the summation of generation plus import.

Figure 27 and Figure 28 show percentage utilisation of feeder pairs with pre-existing and preferred NOP configurations over trial week 1 (1st -6th Oct 2014) and week 2 (7th -13th Oct 2014) under the loss minimisation method (method1). The similarity in the reported feeder loading with the calculated feeder loadings for each of the trial weeks under different configurations is replicated across all the feeder pairs. A full set of these results is shown in Appendix O.

Referring to Figure 27 and Figure 28 in the pre-existing configuration, the maximum percentage feeder utilisation of Newton Rd Way 05 (NR05) is around 24% (pre-existing configuration shown as blue line in both figures). Adjusting the open point position causes load to be transferred from Newton Road way 05 to Winslow Way 03 (WS03), and as a result, peak utilisation of NR05 falls to around 19%.

However when looking at Winslow way 06 (WS06) and Newton Rd way 08 (NR08) there is a different story. The key difference on this feeder is that at the time of the trial there was approximately 3MW of generation close to Newton Rd Way 08 and as such the feeder current is exporting power back through the primary substation. The preferred NOP moves towards Newton Road and this change leads to the increase of feeder utilisation of feeder WS06 and NR08. The former is because of the additional loads transfer to WS06 and the latter is from the increased power fed back to the upper grid.

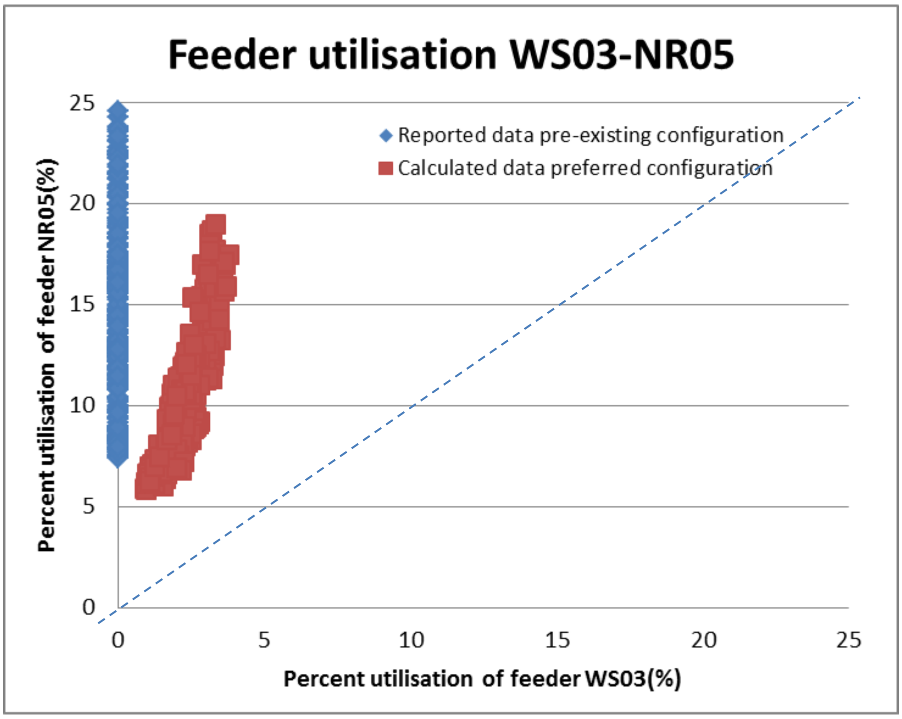


Figure 27: Measured and estimated feeder utilisation of WS03 and NR05 over week 1

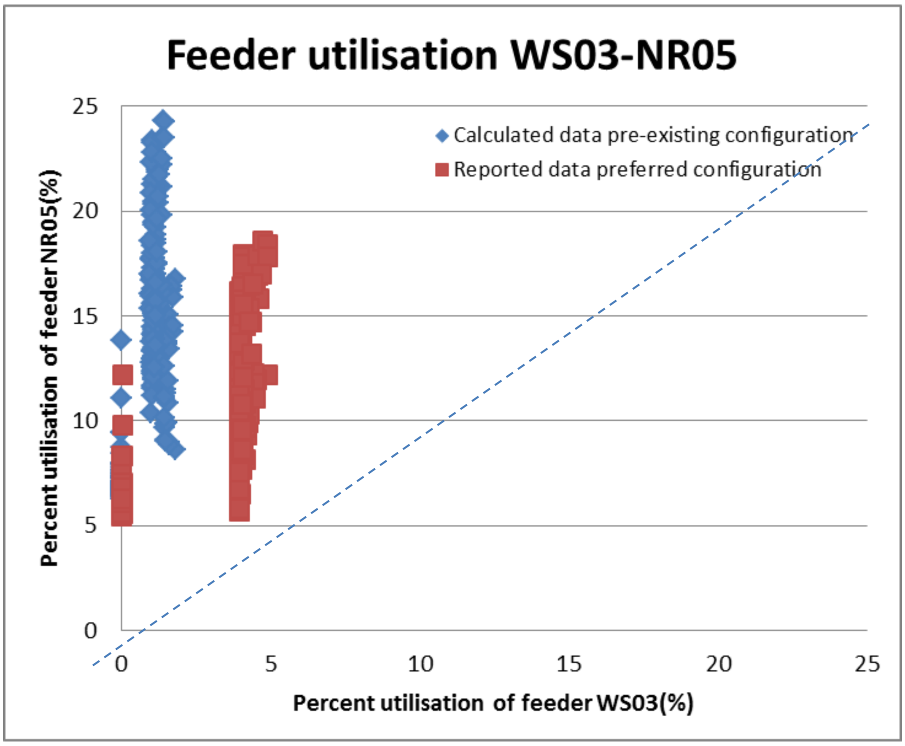


Figure 28: Measured and estimated feeder utilisation of WS03 and NR05 over week 2

Overall, the feeder utilisation balance is improved on feeder WS03, WS05 and WS04, whilst the situation is worse for WS06 and NR08 (impact of method1 on feeder utilisation). Due to the fact that WS06 has a lower rating than the other feeders this means that overall the headroom on the highest percentage loaded feeder is worsened.

LP 30.	Method 1 is designed to minimise losses and therefore there is no explicit input into the process around feeder rating and capacity headroom. However a smaller rated cable tends to have higher impedance and therefore to reduce losses it is helpful when less current flows along higher impedance networks. Consequently method 1 cannot be used to deliberately increase capacity headroom on a feeder – but this may occur fortuitously.

6.2.3 Method 2: Overhead trial network results

As described in Section 5.3, a different preferred configuration was applied to the Network over a week long period in April 2015. This was specifically aimed at improving percentage feeder utilisation.

Table 10 summarises the results obtained and plotted for the key feeder pairs WS03/NR05 and WS06/NR08 (week 1 pre-existing NOP configuration in place and week 2 – preferred NOP configuration in place).

	Existing configuration (a)		Preferred configuration (b)	
	Measured total feeder current (peak)	Calculated total feeder current (peak)	Measured total feeder current (peak)	Calculated total feeder current (peak)
Week 1	361	361	-	355
Week 2	-	342	336	336

Table 10: Method 2 Feeder current validation for the overhead line Network

In each trial period, the calculated feeder current varies slightly with the NOP configuration because the load and losses vary.

Figure 29 and Figure 30 show that with the existing configuration, the percentage feeder utilisation for NR05 is around 24%. Adjusting the open point position causes load to be transferred from Newton Road way 05 to Winslow Way 03 with the result that the skew in feeder utilisation (from the line of balance – dashed line) decreases and the percentage utilisation on Newton Rd Way 05 reduces to a peak of around 10%. This deliberately frees up around 15% of extra capacity on this feeder. This is much higher than the fortuitous 5% extra capacity freed from method 1 and shown in Figure 27 and Figure 28.

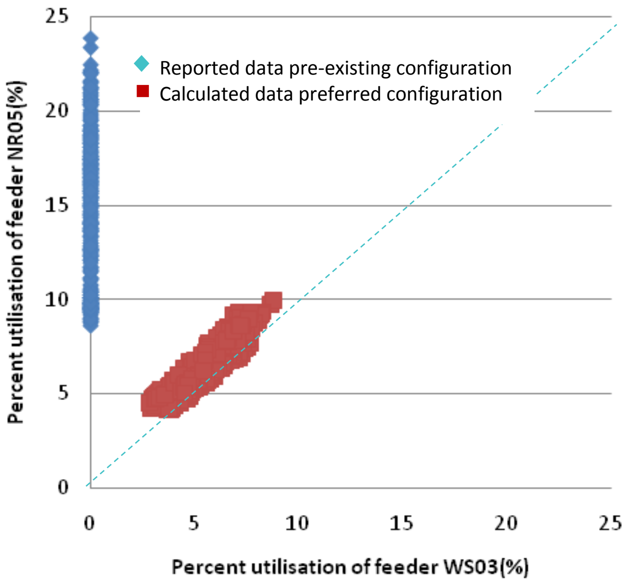


Figure 29: Feeder utilisation for week 1 (WS03/NR05)

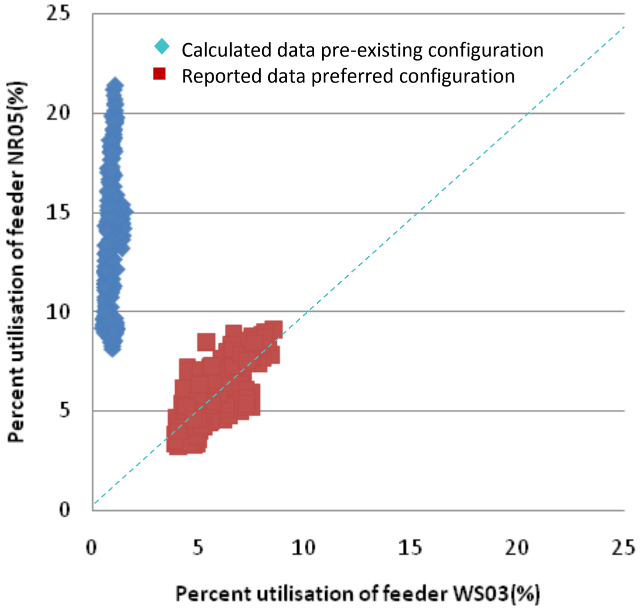


Figure 30: Feeder utilisation for week 2 (WS03/NR05)

Figure 31 and Figure 32 are equivalent curves for feeder pair Winslow way 06 and Newton Rd way 08. The key difference on this feeder is that there is approx. 5MW of generation close to Newton Rd Way 08 and as such the feeder current is exporting power back through the primary substation. The trial results suggest that there is still scope for improving the utilisation of Winslow Way 06 by around 10%, whilst smaller changes to the utilisation to Newton Rd Way 08 of about 5% exist.

The plots of the remaining feeder pairs are shown in Appendix Q.

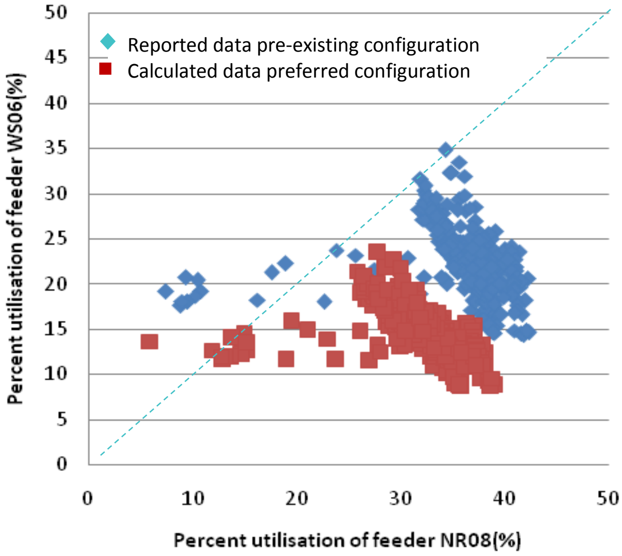


Figure 31: Feeder utilisation for week 1 (NR08/WS06)

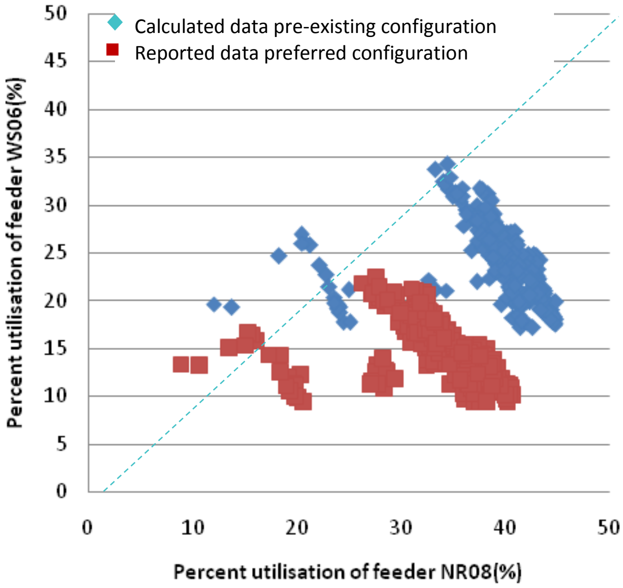


Figure 32: Feeder utilisation for week 2 (NR08/WS06)

LP 31.	Experimental measurement and subsequent analysis of moving the open points on a trial Distribution Network have shown there is scope to add additional capacity headroom to Network feeders to assist with new/altered connections.

- These connections may be either in the form of load or generation. However, it may be necessary to consider these separately as increasing headroom for new generation results in trying to use the power produced locally and this may be constrained by line or cable ratings within tapered Networks rather than by feeder ratings close to the primary substation.

6.2.4 Method 2: Cable trial network

As described in Section 5.4, a different preferred configuration was applied to the Network over a week long period in June 2015. This was specifically aimed at improving percentage feeder utilisation. Table 11 summarises the results obtained, with key feeder pairs plotted in Figure 33 and Figure 34.

	Existing configuration (a)		Preferred configuration (b)	
	Measured total feeder current (peak)	Calculated total feeder current (peak)	Measured total feeder current (peak)	Calculated total feeder current (peak)
Week 1	645	645	-	645
Week 2	-	609	609	609

Table 11: Method 2 Feeder current validation for the cable Network

Figure 33 (week 1) and Figure 34 (week 2) are for feeder pair Marlborough Street way 07/ Newport Pagnell Way 08 and show that with the existing configuration (blue plot), the highest % feeder utilisation of MS07 is around 42%. Adjusting the open point position (red plot) causes load to be transferred from MS07 to NP08 with the result that the skew in feeder utilisation decreases and the peak percentage utilisation on MS07 reduces to around 33%. This frees up around 9% of extra capacity on this feeder.

The remaining feeder results are given in Appendix R and all show a similar level of closeness between calculated and reported feeder currents between the two different weeks.

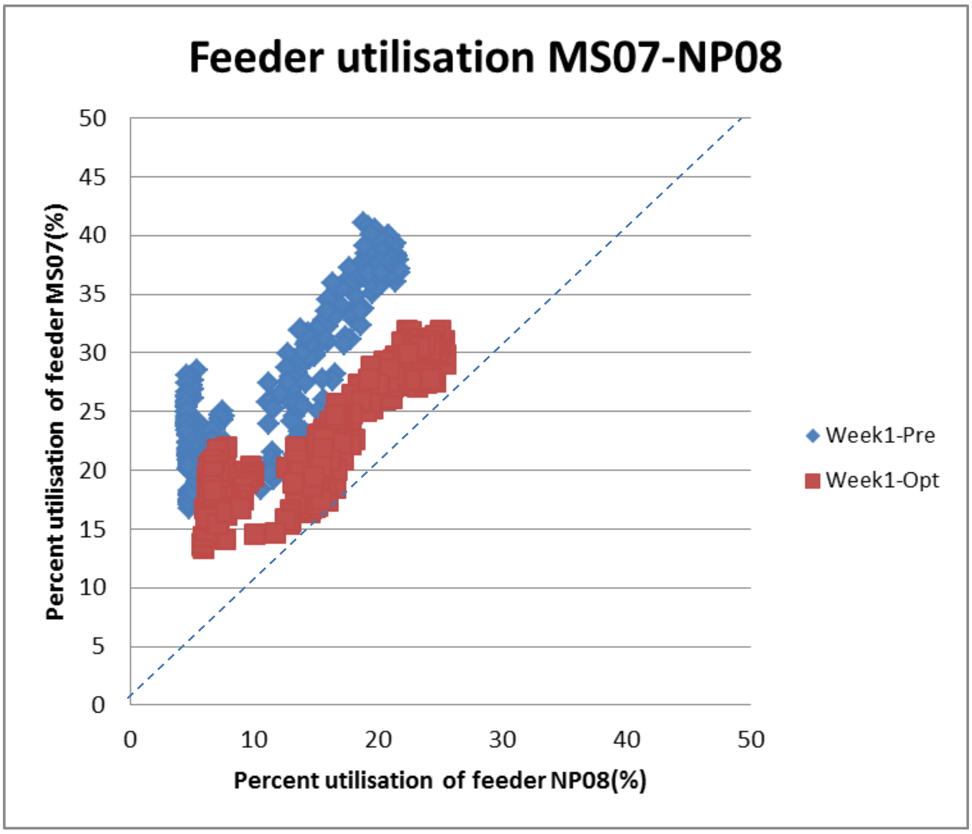


Figure 33 Feeder utilisation with pre-existing NOP between MS07 and NP08

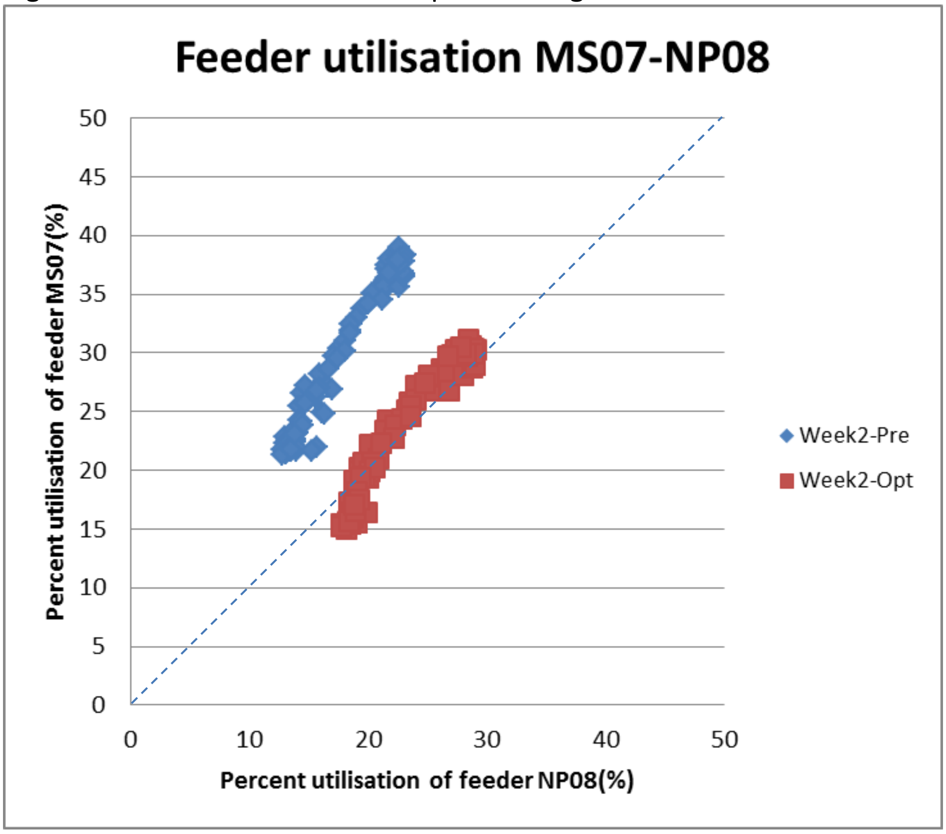


Figure 34 Feeder utilisation with optimised NOP between MS07 and NP08

Due to the network topology limitation, load utilisation balancing is a little worse for one feeder pair, but clear additional headroom could be achieved with method 2 for the rest feeder pairs.

LP 32.	It is difficult to directly focus on increasing headroom by a fixed amount on one feeder as Network topology and the interaction between feeders makes this a complex process with no guarantee of improvements. Wherever a feeder gains in terms of headroom capacity an interconnected feeder must have a higher load and therefore decrease its headroom.

6.3 Modelled trial benefits

6.3.1 Feeder utilisation

Overhead network

High level indicators of feeder utilisation for method 1 preferred NOPs and the overhead line network are shown in Table 12. This covers the period when the preferred NOP configuration was active. Results based on measurement have a white background, and modelled results are shown in grey. Comparison of results for periods with the preferred NOP configuration, and for the preceding period with the pre-existing NOP configuration show that the (greyed) modelled results provide a good indication of what would have occurred if the alternate configurations had been in place, and hence it is valid to compare results within Table 12 and Appendix S.1 , and draw conclusions.

NOP configuration	Maximum feeder utilisation (%) across all periods				
	WS03	WS06	NR04	NR05	NR08
Pre-existing configuration 0	2	39	18	24	23
Configuration 1	5	42	20	19	23
Configuration 2	5	42	20	15	23

Table 12: Method 1 - Calculated highest feeder utilisations for trial period week 2 for overhead line network

Analysis of these results suggests that:

- Implemented Configuration 1 increased utilisation of WS03, WS06, and NR04, and reduced maximum utilisation on NR05 while NR08 was largely unchanged.
- Modelled Configuration 2 essentially achieved the same results as configuration 1, though further reduces maximum feeder utilisation for NR05. There was little difference on highest power loading between configuration 2 and configuration3.
- The rating of the branch with highest rating (W06, 4.38MVA) is around half of the other feeder ratings (8.1 – 9.66MVA).

LP 33.	Feeder Utilisation varies seasonally and over the course of the trial varied by around 10% (Looking at the difference in feeder currents under the nominal configurations over different trial periods). There were also variations due to the addition of more generation.

LP 34.	It is not possible to achieve all the desired benefits simultaneously. The choice of method to calculate the NOP location will need to define which benefit is most desirable in order to focus the analysis.

Method 2 is designed to increase the headroom on pre-determined feeders within the Network. Table 13 shows the corresponding results.

NOP configuration	Maximum feeder utilisation (%) across all periods				
	WS03	WS06	NR04	NR05	NR08
Pre-existing configuration 0	2	34	15	21	45
Configuration 1	9	22	17	9	41

Table 13: Method 2 - Calculated highest feeder utilisations for trial period week 2 for overhead line network

Analysis of these results suggests that:

- Implementing the preferred NOP configuration reduced the loading on the three more heavily loaded feeders (NR08, WS06 and NR05);
- Correspondingly, the remaining two feeders became more heavily loaded.

Whilst comparison between these results for method 1 and method 2 algorithms for selecting NOPs can only be done on a trend basis[3], it is clear that Method 2 provided a superior means of transferring load from the more heavily loaded feeders to the more lightly loaded feeders.

LP 35.	Although it is possible to reduce loading on a feeder this reduction can be limited by Network configuration constraints

Although a reduction in the two more heavily loaded circuits was achieved. Only a slight reduction in loading on NR08 was achieved compared to a greater reduction on the less heavily loaded WS06 circuit.

Underground network

High level indicators of feeder utilisation for method 1 preferred NOPs and the overhead line network are shown in Table 14, and are shown on the same basis as for the overhead network above.

[3] The trials were carried at different time of year, and therefore the loads and generation were different.

NOP configuration	Maximum feeder utilisation (%)						
	NP03	NP07	NP08	NP09	MS01	MS07	MS10
Pre-existing configuration	18	33	25	11	19	51	20
Configuration 1	16	39	30	7	28	41	24
Configuration 2	16	36	28	15	28	43	22

Table 14: Method 1 - Calculated highest feeder utilisations for trial periods 17-24 Jun 2014 for Cable Network

Analysis of these results suggests that:

- Configuration 1 reduced maximum utilisation of the most heavily loaded feeder (MS07), though
- load was transferred to NP07 despite this being the second most heavily loaded feeder; and
- Configuration 2 performed similarly to configuration 1.

Table 15 shows the corresponding results for Method 2 identified NOPs for the cable network.

NOP configuration	Maximum feeder utilisation (%)						
	NP03	NP07	NP08	NP09	MS01	MS07	MS10
Pre-existing configuration	18	32	23	9	17	39	19
Configuration 2	23	28	29	13	17	31	16

Table 15: Method 2 - Calculated highest feeder utilisations for trial periods for Cable Network

Analysis of these results suggests that:

- The implemented configuration (1) reduced maximum utilisation of the two most heavily loaded feeders (MS07 and NP07), plus a load reduction on MS10; with
- Corresponding increases in load on other feeders;
- This is most noticeable on NP08, which is a feeder pair with MS07

Comparison of Method 1 and Method 2 results again shows that that Method 2 gave superior improvements in balancing load and creating 11kV network capacity for the trial test periods.

The results of modelling across the year using the representative days (Table 16) suggests that the Method 2 leads to improvement in capacity headroom around the year. This can be seen in Table 16.

Representative Period		Max Feeder utilisation (%)	
		Nominal	Method 2
Winter	Weekday	40.4	28.1
	Weekend	40.4	28.4
Spring	Weekday	29.1	19.7
	Weekend	28.8	19.6
Summer	Weekday	24.1	17.6
	Weekend	23.7	18.4
High Summer	Weekday	24.6	16
	Weekend	23.2	16.1
Autumn	Weekday	35.4	24.5
	Weekend	33.1	23

Table 16: Method 2 maximum feeder utilisation

In summary, the Method 2 algorithm leads to superior load balancing and capacity headroom improvements compared to Method 1. For the ALT technique trial:

- On the overhead network an improvement of four percentage points for the most heavily loaded feeder, and twelve percentage points for the second most heavily loaded feeder were seen during the ALT technique trial test period ; and
- On the underground network a reduction of eight percentage points was achieved on the most heavily loaded feeder, and the three most heavily loaded feeders balanced to within three percentage points were seen during the ALT technique trial test period; and
- Reductions in maximum (of any) feeder loading can be expected around the year using this approach.

6.3.2 Losses

A summary of the calculated change in losses is shown below with more detailed results in Appendix S.2

Method	Network	Change in losses – trial tests
1	OHL	-12%
1	Cable	-8%
2	OHL	+30%
2	Cable	+0.8%

Table 17 : Comparison of calculated losses variation under trial configuration

It should be noted that the calculated losses are based on the actual measured total feeder loads in that period, and the assumed distribution of load along the feeders. It is important to recognise that the calculated losses could be different if the actual distribution of loads along the feeders differed substantially.

Pulling the losses analysis together, data from this trial suggests for the technique trial networks:

LP 36.	A revised configuration of NOPs compared to the pre-existing configuration should lead to modest improvements in network losses

LP 37.	Improvements are found to be up to 12% using method 1 (loss minimisation) configurations.

LP 38.	Losses were found to increase using method 2 (capacity headroom maximisation).

LP 39.	It is not possible to directly measure losses on the Network without measurement at each substation. Therefore losses must be modelled. More studies and measurements are detailed on WPD NIA project.

LP 40.	Only marginal improvements in losses are available by having an ideal set of NOP's as opposed to the nearest set of practical NOP's (using method 1 to set the configuration of the NOP's).

The following table shows a summary of the calculated benefits range of dynamically moving the NOP across a day/week and season. More detailed data is given in Appendix S.5.

Method	Network	Change in losses - trial modelling across year
1	OHL	-20 % to -14%
1	Cable	-11% to -4%

Table 18 : Comparison of benefit gains with seasonal NOP variation.

It should be noted that this range merely shows the range of values seen at difference times of day/days of the week/across seasons. Whilst this suggests that there may be some additional benefit associated with more frequent switching, it is considered that further load monitoring would have to occur around the indicated switching points to conclude if these additional benefits really existed, and their magnitude relative to the complexity that would be required to capture them.

6.3.3 Minimal node voltage

A summary of the change in voltage is shown below, where a positive change indicates an improvement in system voltage on the feeder with the lower voltage, with more detailed data in Appendix S.3. It should be noted that as load is transferred away from one feeder to improve voltage, that same load is added to another feeder (at the end of the feeder) and worsens that end-of-feeder voltage.

Method	Network	Voltage limits increase
1	OHL	+0.3%
1	Cable	0%
2	OHL	-3%
2	Cable	-0.5%

Table 19: Comparison of minimum bus voltage variation

It should be noted that the calculated voltages are based on the actual measured total feeder loads in that period, and the assumed distribution of load along the feeders. It is important to recognise that the voltages could be different if the actual distribution of loads along the feeders were not as assumed. The voltage at the primary substations is modelled as 11.3kV.

There is no significant change in voltage on the cable network. However, there are slight improvements on the OHL network under method 1

Inspection of these calculated overhead line voltage values suggests that the difference in minimum circuit voltage is improved using the configuration determined by method 1 because this circuit is located where the area is rural and there is a larger voltage drop along lengths of overhead line.

LP 41.	Voltage improvement is possible using ALT under method 1, but is more noticeable on a rural overhead line Network. However improvements are minimal.

This improvement is expected as the NOP search algorithm is based on minimum voltage. The change in voltage profile across a branch of the network can be seen by comparing Figure 36 and Figure 35. The voltage from Winslow has dropped as more loads are shifted onto this feeder. However the voltage on the more heavily loaded connected Newton Rd feeder has improved with the shift in open point position.

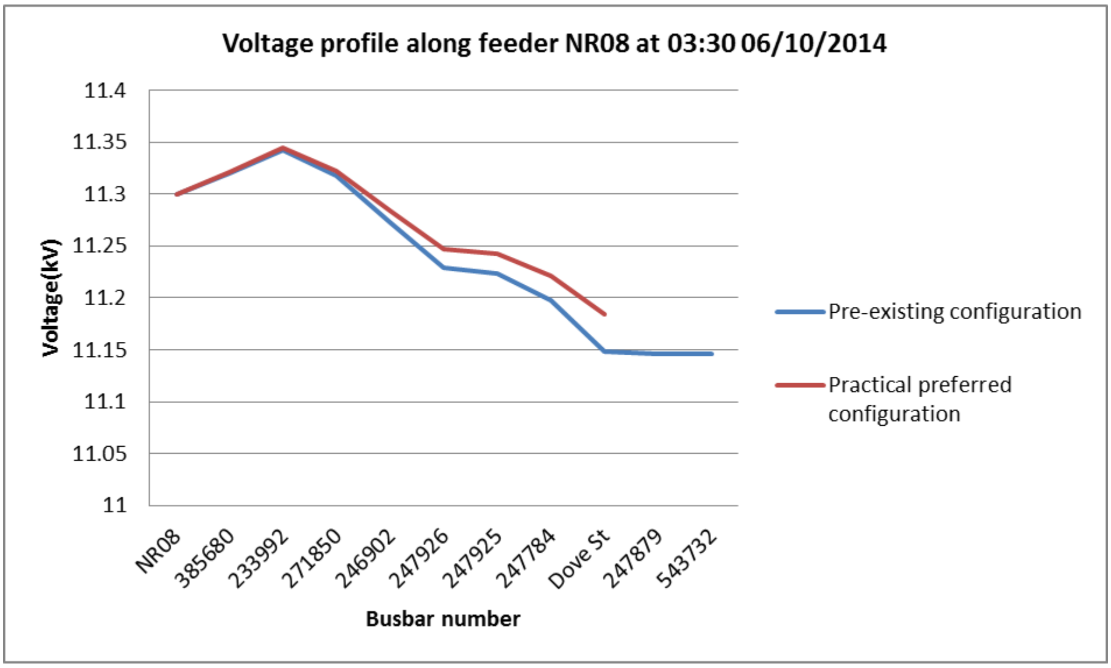


Figure 35 : Voltage profile along Newton Rd feeder 6 showing changes to voltage as the feeder is re-configured under method 1

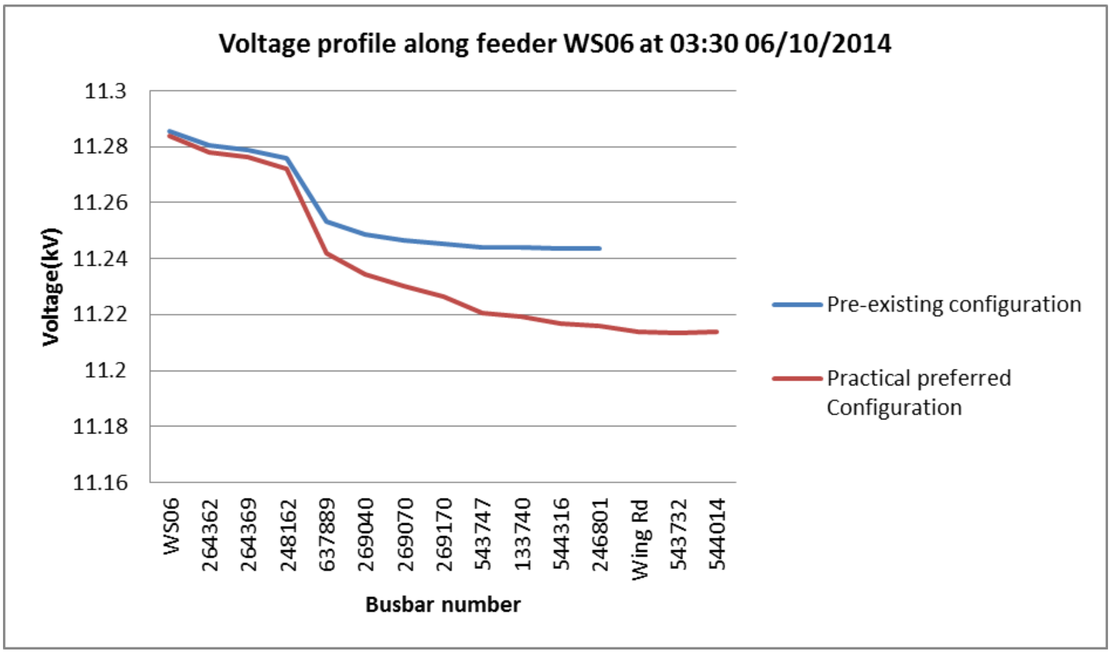


Figure 36 : Voltage profile along Winslow feeder 6 showing changes to voltage as the feeder is re-configured under method 1

It can be seen in Table 19 that under the method 2 results the voltage with the preferred configuration is lower than that with pre-existing configuration. To balance the feeder utilisation, some loads are transferred to the feeder with longer distance, which contributes to the voltage drop.

6.3.4 Customer Numbers

A summary of the changes in customer numbers is shown in Appendix S.4

- For overhead lines under method 1 and method 2, customer numbers on 3 of the 5 feeders go up including the feeder with the largest pre-existing number of customers (from 2059 to 2326).
- For underground cables under method 1 customer numbers on 4 of the 7 feeders go up including the feeder with the largest pre-existing number of customers (from 2042 to 2747).
- For underground cables under method 2 customer numbers on 3 of the 7 feeders go up , in this instance the most heavily populated feeder number goes down (from 2042 to 1678).

Changes to customer number are consequential in this analysis i.e. Customer numbers were not a factor affecting either method 1 or method 2 algorithms.

LP 42.	Potentially more customers are at risk of being impacted by a fault if the Network is reconfigured to reduce losses or increase capacity headroom.

SECTION 7

Cross-technique Comparison[4]

[4] This section is common to all the engineering technique Final Reports.

Table 20 provides a high level summary of which techniques impact what network metric, with the remainder of the section providing comparison of the DAR Cable technique with other trials, on a network-metric basis.

	DAR - OHL	DAR-Tx	DAR-Cables	ALT	Mesh	Energy Storage
Thermal limits /capacity headroom	✓	✓	✓	✓	~	✓
Voltage limits	No impact	No impact	No impact	✓	~	✓
Fault levels	No impact	No impact	No impact	No impact	×	×
PQ	No impact	No impact	No impact	~	~	✓
Enablement of DG	✓	✓	✓	✓	✓	✓
Losses	×	×	×	✓	✓	×
CI/CMLs	No impact	No impact	No impact	~	~	No impact
Grid/ network services	No impact	No impact	No impact	No impact	No impact	✓

Key: ✓Positive impact; ×negative impact; ~ network dependant, may have positive or negative impact

Table 20: Cross-technique comparison of impact.

Network capacity:

- All techniques altered capacity on the network;
- DAR evaluates capacity more accurately than static ratings which may suggest additional or in some cases less capacity. OHLs are predominately affected by wind speed/direction meaning significant variations occur both across seasons and within short time scales (minutes). When this variability of rating is combined with the low thermal capacities of OHLs (i.e. the OHL temperatures respond rapidly to the environmental changes), taking advantage of this technique is limited to particular circumstances. The dynamic ratings of both cables and transformers are dependent on ambient temperatures, meaning diurnal (for transformers only) and seasonal variations are clearly present, and the larger associated thermal capacities means short-time duration changes in ambient conditions cause less short term variability in asset ampacity;
- ALT and mesh shift load from one part of a network to another, thereby potentially relieving constraints. ALT offers a far more intuitive mechanism, whilst mesh is continually dynamic by its very nature. The extent to which benefits exist is highly dependent on the connectivity of any candidate network, and loads/generation connected to the network, and the extent to which the loads vary relative to each other; and
- Energy storage shifts load in time, reducing load at a capacity constrained key point in time, only to increase the load at a less critical point in time. The specified power and storage energy capacity clearly need to be appropriately matched to the network load; and adaptive triggering is required to deal with individually daily variations in load, to optimise the impact that the installed system can have on the network.

Energy Storage may complement DAR by providing a mechanism to alter load patterns such that constrained assets might make the best use of available ampacity.

Voltage:

- Three of the techniques offer some potential for benefits (ALT, Mesh, ES);
- ALT demonstrated the largest benefit (4%), on some of the rural circuits that were trialled, but no significant benefit was found on urban circuits;
- Mesh considered a small urban network and for this example there was no significant impact on voltage;
- In general the voltage benefit of the ALT and mesh techniques networks will depend on the voltage difference across pre-existing NOPs, and does not directly address voltage issues at the end of branches
- The installed energy storage systems achieved little impact. In general, the reactive power capacity in relation to the magnitude and power factor of the adjacent load is modest, and can be expected to be expensive to deliver for this benefit alone.

Fault level:

- As is clearly already recognised, introducing generation (including ES) to a network will ordinarily increase fault level, in this instance the ES were small compared to pre-existing fault levels, and so had negligible impact. Meshed networks will also increase fault level due to the reduced circuit impedance. For the mesh technique trial, this was within the ratings of all circuit equipment.

Power Quality (PQ):

- Mesh trials showed no discernible impact on power quality. Super-position theory and the feeding of harmonic loads via different sources means that harmonics presently fed from one source could be fed from two sources (depending on Network impedances), however, it is unlikely that larger scale trials will show any marked appreciable benefits as the majority of loads are within limits defined by standards and as such it will be difficult to differentiate small changes;
- The installed energy storage equipment did not specifically have functionality aimed at improving PQ. At one site, improvement was noted, however this was a beneficial coincidence arising from the nature of a local (within standards) PQ disturbance and the inductance/capacitance smoothing network in the Energy storage system;
- More targeted studies of a network that has a known PQ issue could be identified to further examine the potential of mesh/ALT techniques to beneficially impact this issue.

Enablement of DG:

- This was not specifically studied as part of the engineering trials (e.g. interaction between the engineering techniques and DG was not designed into the trials);
- Whilst not a direct focus of the FALCON trials, it is clear that DAR systems may offer potential benefit to distributed generation, but is highly dependent on circumstances.

For example, OHL DAR can increase export from OH connected wind farms on a windy day; but solar farm output peaks occur on clear summer days when DAR OHL is less likely to provide additional benefit;

- ALT may facilitate the connection of more distributed generation. However, this needs to be looked at on a case-by-case basis as the location of the generation along the feeder, in relation to the ratings and load, can have an impact. Where the generation is close to the source (such as in the FALCON ALT OHL trial), there is scope to add a significant amount of generation so that the feeder is able to export at the Primary and also meet the load requirements along this feeder. The nominal location for the open point may well be different between when the generation is running or is off and this may impact other metrics such as losses and voltage regulation if generation operating condition is not considered.
- Meshing may facilitate the connection of more distributed generation by providing a second export route in certain scenarios, thus saving on line and cable upgrades. Modelling also indicates that there may be cost savings from reductions in feeder losses when meshing a network with DG connected to one feeder. However, the benefits of reduced losses would have to be compared on a case-by-case basis with the costs of more complex protection required for meshing (potentially necessitating replacement of existing protection relays as well as new relays).
- ES systems offer potential benefit to distributed generation. Examples of this include: peak generation lopping - storage of peak energy production (say above connection agreement levels) for later injection to the grid; and storage of energy to allow market arbitrage.

Losses

- As discussed in the preceding technique-trial specific section, ALT and Mesh offer some potential, though the magnitude is network specific.
- The trialled ES systems increased losses, and DAR will tend to increase losses if higher circuit loads are facilitated.

CIs and CMLs

- ALT changes NOP positions and consequently affects numbers of connected customers per feeder. The trial algorithms:
  - Increased one feeder numbers by 15% (whilst optimising capacity headroom) on a rural/OHL network; and
  - Increased one feeder numbers by 50% (whilst optimising losses/voltage) on an urban/cable network.
- Meshing networks does not improve customer security as such; the improvement only occurs if additional automatic sectioning/unitising occurs beyond that offered by the pre-existing NOP. Due to communication system limitations, the implemented trials did not increase the number of sections, essentially maintaining the pre-existing customer security.

Grid/network Services:

Whilst these trials have demonstrated that frequency response is possible with the ES technique, a marketable service is not fully delivered by the installed equipment. In addition, further work would be required to put DNO owned energy storage on an appropriate commercial basis. Refer to the WPD Solar Store NIA project.

SECTION 8

Conclusions and Recommendations

Key findings

Improvements in 11kV capacity (at first branch out of the primary) are possible. These improvements are dependent on the algorithm used, method 2 gave superior results to method 1. On the overhead network an improvement of four percentage points for the most heavily loaded feeder, and twelve percentage points for the second most heavily loaded feeder were seen during the ALT technique trial test period. On the underground network a reduction of eight percentage points was achieved on the most heavily loaded feeder, and the three most heavily loaded feeders balanced to within three percentage points were seen during the ALT technique trial test period. Reductions in maximum (of any) feeder loading can be expected around the year using this approach.

Improvements in 11kV losses are also possible. Improvements are again dependent on the algorithm used, method 1 improved losses, method 1 (design to improve capacity) lead to greater reduction in losses. Improvements are found to be up to 12% using method 1. It is not practicable to directly measure losses on the Network without measurement at each substation. Therefore losses, and benefits in losses, must be modelled.

Voltage improvement was also achieved under method 1. This is more noticeable on a rural overhead line Network, and was marginal in magnitude on the trial network;

Customer numbers per feeder varied consequentially according to the algorithms developed to improve losses/voltage, and capacity. Depending on the specific network, potentially more customers are at risk of being impacted by a fault if the Network is reconfigured to reduce losses or increase capacity headroom. This could be mitigated through implementation of along-feeder staged protection.

It seems possible that much of the improvements that have been indicated from these technique trials could be captured through one-off adjustment to NOPs, though the trials do indicate that further (more marginal) benefit may be obtained by implementing within day, over the week, and across season changes to NOPs. Where the analysis shows potential variation in switching points (across the day, within week or across seasons) then the potential switching points are closely clustered. It is considered that further load monitoring would have to occur around the indicated switching points to conclude if these additional benefits really existed, and their magnitude relative to the complexity that would be required to capture them.

Whilst networks could be optimised to improve capacity ahead of need, there is no benefit in doing this in preference to optimising for losses/voltage. ALT could be considered as a strategy for improving capacity headroom, but only as feeders approach thermal limits.

Other key learning

Extensive data collection, NOP selection algorithms, modelling and model validation are all required to identify alternative NOP positions. This includes up-to-date network models, accurate technical parameters for the network, and models/measurements of load and particularly generation. The accuracy of outcome (NOP positions) is highly dependent on the load measurement/model used.

This detailed modelling should be completed ahead of determining the need for/location of additional remote switching. These trial results showed that preferred NOP positions were either found at specific points, or over a number of adjacent switches, rather than generally distributed across the network. Remote switching (and potentially additional circuit sectioning points on OHL networks) should then be installed at these modelled points of interest/benefit.

Benefit assessment, and validation of the assessed benefit, is not straightforward. It is not possible to directly measure an improvement that would arise from implementing an alternative NOP configuration. The loads will always be marginally difference between the two test periods, and inference of improvement from modelled results is the basis of our findings. A novel method of validating benefit assessment has been developed and used.

The fact that two algorithms were required to optimise for different criteria illustrates well the complexity inherent in modelling for ALT. It is paramount to appreciate that the indicated ALT benefits are not all simultaneously realisable.

Changing open point locations to improve capacity on the first branch out of the primary may have adverse impacts on branch loading close to pre-existing NOPs, if the network is tapered.

Because of the nature of overhead networks (permanently connected pole mounted transformers) there are less network switching points, and therefore the resolution of changes for the overhead network is coarser compared to the UG network. That being said it is generally cheaper to install switches at optimal points on the overhead network compared to establishing ground mounted switching points on the underground network. Had detailed analysis been carried out first we could have had greater success at placing switches in more useful locations.

There is some possibility that the variation of preferred NOPs is related to the loads of small numbers of larger consumers. This raises the possibility that the exact location of the preferred open point may be directly related to the load at a single site. This in turn raises the possibility of defining real-time preferred open points based on single site or switching point measurements with trigger points, though thresholds/trigger points for change would have to be determined through extensive modelling and/or practical testing. Benefit analysis could only be undertaken with network modelling.

Generation potentially has a very significant impact on the network, and preferred open points. It is therefore essential to understand its running regime.

Future variation in the magnitude and profile of loads and connection/change in distributed generation implies the need for ongoing monitoring/re-assessment of optimum NOPs.

Further development and validation of the technique needs to occur before it could be used in a planning environment. A potential route would be: deployment of the technique on a section of network that has capacity issues, and develop algorithm/solutions in collaboration with local planners.

Recommendations

It is recommended that the FALCON NOP positions are considered for adoption on the trial network, subject to review and mitigation of customer number changes

ALT appears to offer potential to reduce losses through a one-off / occasional re-assessment of NOP position across the network. Further work would be required to complete specification of cross-network data requirements, and consolidate modelling algorithms for bulk network assessment purposes. It is recommended that the potential of such an exercise is further considered.

ALT also appears to offer potential to optimise a network that is approaching thermal limits. It is recommended that a candidate portion of network could be assessed using this technique to trial actual solution provision, where network is currently approaching/is at limits.

Appendices

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B Initial Learning Objectives

	A	B	C
1	Where can this be implemented	Limitations of practicality	Costs
2	Understanding of magnitude of feeder imbalance	Understanding variation in feeder imbalance	Benefits of manufacturer installed automation versus retrofitted automation
3	Optimum number and location of switches	Are existing models of feeder load accurate enough to predict scheme outcome?	What are the power and carbon savings
4	Do peaks and troughs in load across two feeders occur together	Length of time to install	Usefulness of technique across two primaries
5	Applications to support 33kV network	Differences between pre and post operation	Changes to switch gear specification
6	Increased functionality required within NMS for operation	How this techniques can facilitate extra generation on the Network	Is it more applicable on a Network with variable load
7	How quantifiable is the increase in network utilisation	How smart does the network optimisation need to be	Do you balance for voltage, losses, customers or current?
8	Should there be a limit to the number of switching operations per day	Any changes to DSR	Training required for control/network operations/planning

C Literature review

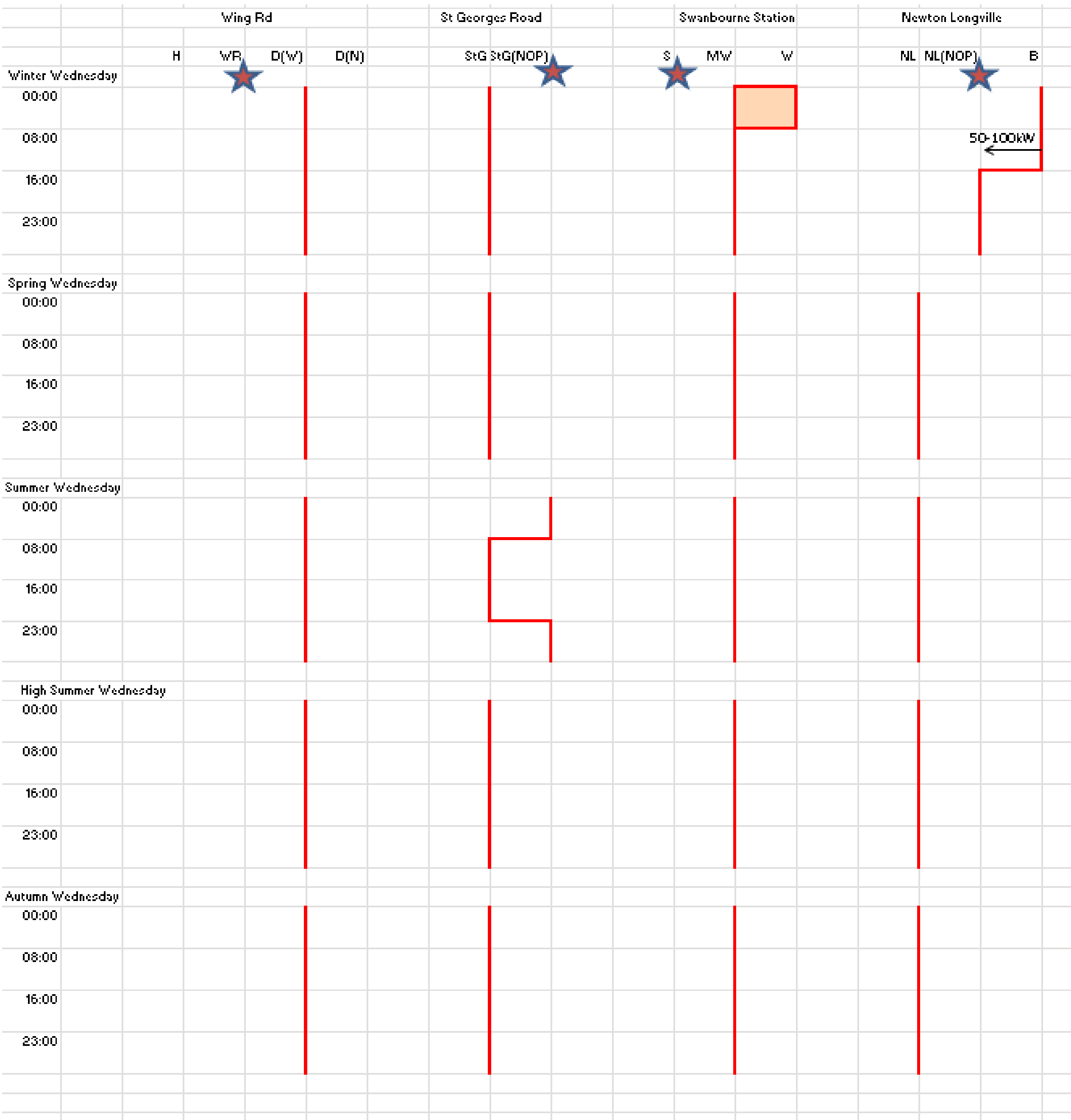
Ref.	Model	Configuration method	Test Network	Load distribution	Research Validation
[1]	Multi	Enhanced Gravitational Search Algorithm	IEEE 33 and 70	NA	Loss, NOP configuration and CPU times compared to PSO and GA
[2]	Multi	Fuzzy algorithm with Bellman-Zadeh method	One 96 branches network and a Network with system with 922 branches	NA	Losses and processing time compared to 1 reference.
[3]	Multi	Searching tree with branch exchange technique.	IEEE 33, 69 buses and a large scale instance with 10736 branches	NA	Compare with simulated annealing and genetic algorithm
[4]	Multi	Probabilistic power flow based and active fuzzy optimization with APSO	Taiwan power system with 86 buses, 11 feeders and 96 switches.	NA	Compare with GA and PSO
[5]	Multi	Adaptive modified particle swarm optimisation	A 32 buses system and a hypothetical 69 bus system	Probabilistic load is modelled as stochastic variables.	Compare with GA, PSO and HBMO
[6]	Multi	A binary particle swarm optimization-based search algorithm	33-bus and 123-bus system	NA	NA
[7]	Multi	Operation schemes without detailed algorithm	32 bus	NA	NA
[8]	Multi	Grey correlation analysis in evolutionary programming	3 systems with 5, 4 and 30 feeders respectively.	NA	Compared to fuzzy rule-based method in reference
[9]	Multi	Informed search algorithm in A* family	Two networks in suburban areas in Australia	NA	NA
[10]	Mono	Evolutionary algorithms	A network with 158 switches in Australia	NA	Genetic algorithm and memetic algorithm
[11]	Mono	Mixed-integer convex programming	83 nodes network from Taiwan Power Company and 135 nodes Brazilian network	NA	Compared with the power flow solution

Ref.	Model	Configuration method	Test Network	Load distribution	Research Validation
			and their duplications		
[12]	Multi	sensitivities of the state variables with respect to switching operations	a 16 bus test system and a real scenario of the 15-kV Madrid distribution system	NA	A paper published in 1989
[13]	Mono	Heuristic method based on branch exchanges for network reconfiguration and random walks-based loss estimations	Distribution systems with sizes of up to 10,476 buses	NA	Compared with the results in references
[14]	Mono	Heuristic method based on minimum branch current	Four hypothetical networks with 16, 33, 69 and 96 buses respectively	NA	Compared with the results in references
[15,16]	Mono	Heuristic method based on minimum branch current and neighbour-chain updating mechanisms	Six hypothetical networks with 16, 33, 69 ,96 and 136 buses respectively	NA	
[17]	Mono	Adaptive hybrid genetic algorithm	IEEE 33 nodes and 5 networks from real distribution systems.	Objective is focused on the energy to include demand variations.	Compared with genetic and hybrid genetic algorithm
[22]	Multi	Self-adaptive modification method based on the clonal selection algorithms	IEEE 69 –bus test system	Probabilistic load flow used to capture the uncertainty of loads.	Compared with deterministic framework from references with different methods such as GA, PSO and CSA.
[23]	Multi	Binary particle swarm optimization search method	A simplified three feeder system and an 18-feeder system	Divide annual feeder load curve into multi-periods and optimizes the network for different load levels	PSO
[24]	Mono	Probabilistic load flow for uncertainties in	IEEE 13 node feeder test system	Assumed that the feeder loads can be estimated or	NA

Ref.	Model	Configuration method	Test Network	Load distribution	Research Validation
		loads and DG.		measured	
[25]	Multi	Planning based on genetic algorithms	IEEE 33 buses network	Multiple scenarios are used to incorporate the uncertainties of DG and load response	NA

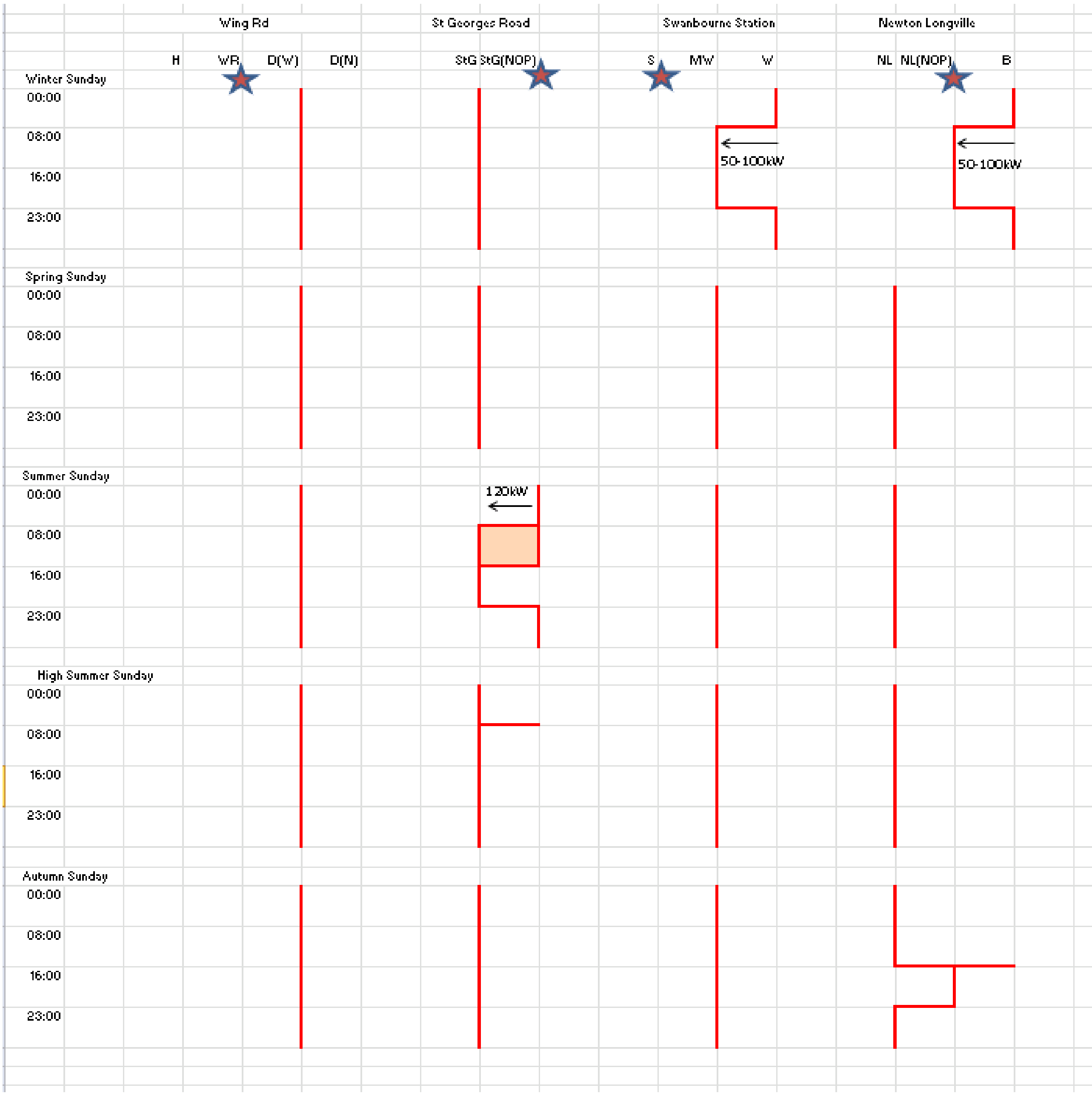
Table 21 : Previously undertaken ALT validation

D Method 1 identified NOPs across the year.



Wednesday (winter, spring, summer, high summer, Autumn)

Figure 37: Graphical representation of potential NOP switching pattern with full generation



Sunday (winter, spring, summer, high summer, Autumn)
Figure 38: Graphical representation of potential NOP switching pattern with full generation

E Variation in preferred NOP positions across the year for cable network using method 2 analysis.

The NOP locations are listed in the following tables for model weekend and weekday respectively. These are determined from the simulation results of the ten typical days with 48 half-hour points each day.

NOP Season	Delaware Drive	Sovereign Drive	Chestnuts	Kara Foods	Wolverton Rd	Hainault Avenue	Ackerman	Beni Foods
Winter	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	STANTONBURY FARM (MS01 side)	Variable within the day	Ackerman(NP09 side)	Retain
Spring	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	STANTONBURY FARM (MS01 side)	Variable within the day	Ackerman(NP09 side)	Retain
Summer	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	STANTONBURY FARM (MS01 side)	Variable within the day	Ackerman(NP09 side)	Retain
High Summer	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	STANTONBURY FARM (MS01 side)	HAINAULT (NP side)	Ackerman(NP09 side)	Retain
Autumn	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	STANTONBURY FARM (MS01 side)	HAINAULT (MS side)	Ackerman(NP09 side)	Retain

Table 22 : Summary of identified changes for UG trials network on typical weekends

NOP Season	Delaware Drive	Sovereign Drive	Chestnuts	Kara Foods	Wolverton Rd	Hainault Avenue	Ackerman	Beni Foods
Winter	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	Variable within the day	Variable within the day	Retain	Retain
Spring	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	Variable within the day	Variable within the day	Retain	Retain
Summer	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	STANTONBURY FARM (MS01 side)	Variable within the day	Retain	Retain
High Summer	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	STANTONBURY FARM (MS01 side)	Variable within the day	Retain	Retain
Autumn	Taylor Nanco (MS side)	Sovereign Dr (MS side)	THE CHESTNUTS (NP side)	Variable within the day	STANTONBURY FARM (MS01 side)	Variable within the day	Retain	Retain

Table 23:Summary of identified changes for UG trials network on typical weekdays

Above optimization results show that

- Delaware Drive
  - No across within week and seasonal variation, though a significant change from the existing NOP, moves to Taylor Nacanco.

  Conclusion: insensitive to seasonal change, within-week change and daily change – recommend NOP moves statically to Taylor Nacanco

- Sovereign Drive
  - No evidence suggesting seasonal variation for weekdays, though NOP moves to Sovereign Dr;

Conclusion: insensitive to seasonal change, within-week change and daily change – recommend NOP moves statically to other side of Sovereign Dr

- Chestnuts
  - No evidence suggesting seasonal variation for weekdays, though NOP moves to other side of current NOP, Chestnuts (Newport Pagnell side);

  Conclusion: insensitive to seasonal change, within-week change and daily change – recommend NOP moves statically to Chestnuts-other side of current NOP

- Kara Foods –sensitive to within day variation. Sensitive to seasonal change and in-week variation

  Conclusion - sensitive to within-day, in-week and seasonal change, preferred NOP scatter among several switch points.

- Wolverton Road
  - no across season variation for weekends, though a significant change from the existing NOP, moves to STANTONBURY FARM (MS01 side). Within-day variation observed on Winter and Spring weekdays.

  Conclusion: mostly insensitive to seasonal change, within-week change and daily change – recommend NOP moves statically to Stantonbury Farm

- Hainault Avenue –sensitive to within day variation. Sensitive to seasonal change and in-week variation

  Conclusion: mostly sensitive to seasonal, within-week and daily change

- Ackerman (closely related to Beni Foods) –Sensitive to within-week variation

  Conclusion & recommendation –insensitive to seasonal change and daily change, sensitive to within-week change. Retain Ackerman on weekdays and move to the other side on weekend

- Beni Foods (closely related to Ackerman)-retain current because the NOP is used to break a loop supplied by the feeder, not practical to balance the load with other feeder at this NOP.

  Conclusion & recommendation – retain nominal NOP

Based on the above, 5 NOPs are fixed including Delaware Drive, Sovereign Drive, Chestnuts, Wolverton Road, and Beni foods. The other 3 NOP vary with time, they are Kara Foods, Hainault Avenue, and Ackerman.

Season	Normal NOP	00:00-08:00	08:00-16:00	16:00-24:00
Winter	Kara Food	Giles FoodsNP03 side-21	Kara Food NP03 side-4	LEGRANDNP03 side-19
	Hainault	B D F TESA NP side-34	HAINAULT NP side-6	B D F TESA NP side-34
Spring	Kara Food	Giles FoodsNP07 side-22	LEGRANDNP03 side-19	Giles FoodsNP03 side- 21
	Hainault	B D F TESA NP side-34	HAINAULT NP side-6	B D F TESA NP side-34
Summer	Kara Food	Giles FoodsNP07 side-22	Giles FoodsNP03 side- 21	Giles FoodsNP03 side- 21
	Hainault	B D F TESA NP side-34	Hainault NP side-6	B D F TESA NP side-34
High Summer	Kara Foods	Giles Foods NP03 side-21	LEGRANDNP03 side-19	LEGRANDNP03 side-19
Autumn	Kara Foods	Giles FoodsNP07 side-22	LEGRANDNP03 side-19	Kara Food NP03 side-4

Table 24: Within-day NOP variation on typical weekends

Above results on weekend NOP variation show that:

- Two NOPs sensitive to with-in day variation are Hainault and Kara Food.
- Regarding Hainault, variations are observed on Winter, Spring and Summer weekends. On early morning and night, the points is consistent at point 34. Whilst the point on most of the day time retain the pre-existing point.
- With regards to Kara Foods, within-day variations are found over the five typical days. Point 22 is preferred on the early morning and 19 is the best for the rest of the time. NOPs are insensitive to seasonal variation.

More NOP variations are observed on typical weekdays.

Season	Normal NOP	00:00-08:00	08:00-16:00	16:00-24:00

Winter	Kara Food	Giles Foods NP07 side-22	TICKFORD ENGINEERING NP07 side-25	Giles FoodsNP03 side- 21
	Wolverton Rd	STANTONBURY FARM MS side-28	STANTONBURY FARM NP side-27	STANTONBURY FARM MS side-28
	Hainault	B D F TESA MS side-35	VOLKSWAGEN NP side-36	B D F TESA NP side-34
Spring	Kara Food	Giles Foods NP07 side-22	7 TANNERS DR NP03 side-23	Giles Foods NP07 side-22
	Wolverton Rd	STANTONBURY FARM MS side-28	Wolverton Rd-5	STANTONBURY FARM MS side-28
	Hainault	B D F TESA NP side-34	B D F TESA MS side-35	B D F TESA NP side-34
Summer	Kara Foods	7 TANNERS DR NP03 side-23	7 TANNERS DR NP03 side-23	Giles Foods NP07 side-22
	Hainault	B D F TESA MS side-35	B D F TESA MS side-35	B D F TESA NP side-34
High Summer	Kara Foods	Giles Foods NP07 side-22	7 TANNERS DR NP03 side-23	Giles Foods NP07 side-22
	Hainault	B D F TESA NP side-34	B D F TESA MS side-35	B D F TESA NP side-34
Autumn	Kara Foods	Giles Foods NP07 side-22	7 TANNERS DR NP03 side-23	Giles Foods NP07 side-22
	Hainault	B D F TESA MS side-35	B D F TESA MS side-35	B D F TESA NP side-34

Table 25 : Within-day NOP variation on typical weekdays

Above results on weekdays NOP variation show that:

- Three NOPs are sensitive to with-in day variation, they are Wolverton Road, Hainault and Kara Food.
- Hainault is sensitive to within-day variation. The optimized NOP are around B D F TESA and the preferred NOP is 34 or 35. The variation are quite similar among seasons and that on weekend.
- With regards to Kara Foods, within day variations are observed. Optimized NOP varies with time among 21, 22 and 23. NOPs are sensitive to seasonal variation and the patterns are similar.

- Daily variations only observed on Winter and Spring weekdays at Wolverton Road, and the variation is mainly on both side of Wolverton Road.

The NOP variation is shown in Figure 39, the NOP variation is confined in certain area and the calculated NOPs are quite near to each other. Points in the middle could be used as a constant trial NOP site.

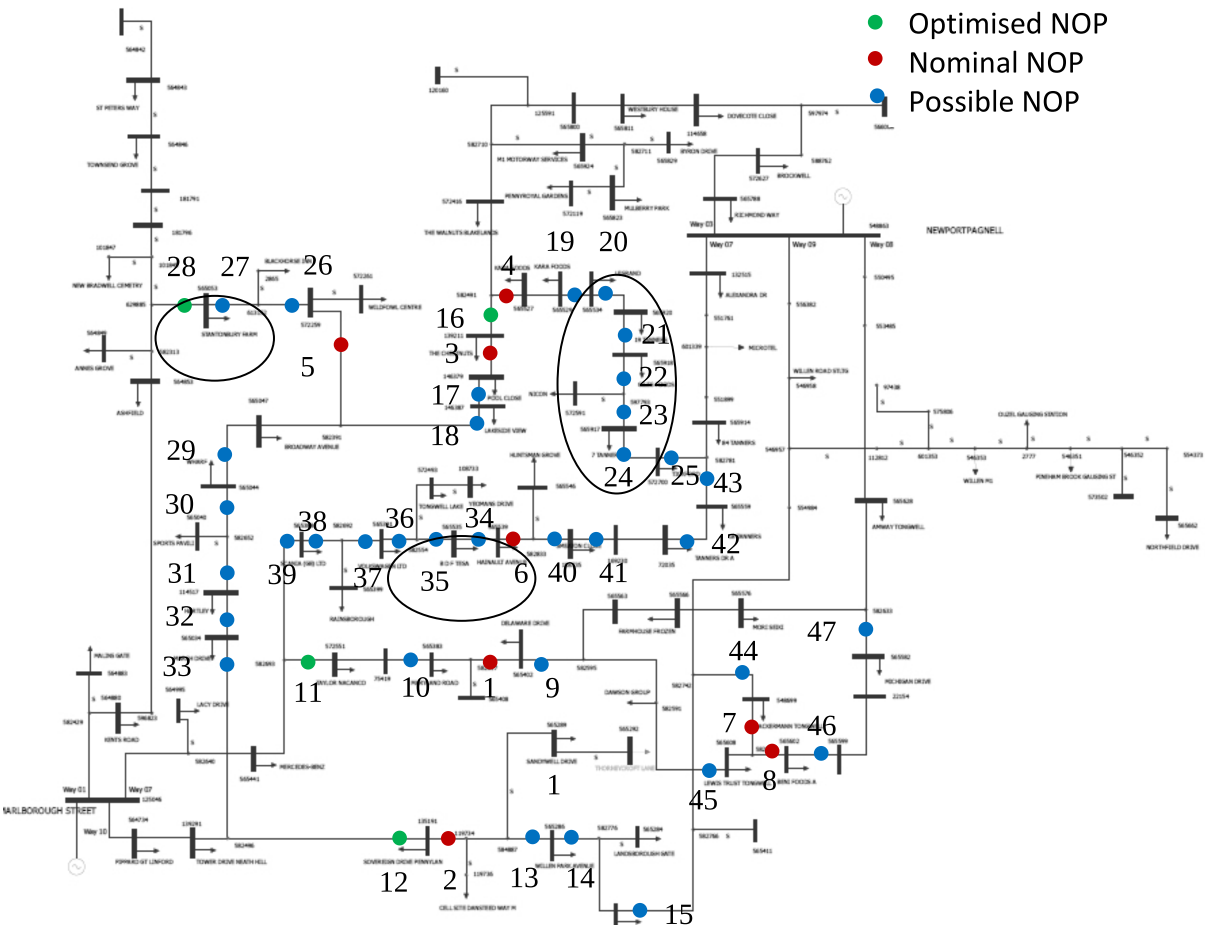


Figure 39 : NOP spread points for Kara Food, Wolverton Rd and Hainault

F Validation

A key data requirement for load flow analysis of the trial network is quantification of individual substation loads. The individual substation loads cumulatively define the total feeder load, and the individual substation loads characterise the distribution of load along a feeder.

In reality, it is very rare that measured data for all substation loads on a portion of network exists, and so estimates of substation load (and how that load varies with time, the load profile) are used within the load flow analysis. Previous work in this area has typically assumed distribution based on maximum demand indications, which has clear potential limitations outside maximum demand periods.

Therefore confidence in projected benefits arising from changes to NOP positions is dependent on the accuracy of estimated load profiles and the resultant distribution of load along feeders.

From this dependency, it follows that the validity of the assumed distribution of load along feeders should be tested to assess the reliance placed on trial results.

Table 26 shows key measurements and calculations arising from the trials. The network is initially prepared in Configuration 1, for the period Week 1. During this period feeder currents are measured (Ref#1), and from this scaled individual substation loads are calculated (Ref#5).

	Configuration 0	Configuration 1
Week 1	**Ref#1 – measured** total circuit current (with config. 0 for week 1), based on measured feeder currents **Ref#5 -** Scaled substation loads (based on estimated sub loads scaled to give a calculated feeder load equal to measured feeder current)	**Ref#2 - Calculated** total circuit current (based Ref#5 and circuit config 1)
Week 2	**Ref#4** - **Calculated** total circuit current (based Ref#6 scaled loads and network configuration 0)	**Ref#3** - **measured** total circuit current (with config. 1 for week 2), based on measured feeder currents **Ref#6 -** Scaled substation loads (based on estimated sub loads scaled to give a calculated feeder load equal to measured feeder

		current)
Table 26: key measurements and calculations arising from trials		

A calculated total circuit load (Ref#2) can then be calculated for network configuration 1 associated with time period Week 1, based on the scaled individual substation loads Ref#5. This calculated total circuit current is shown in a greyed cell in Table 26 to indicate that it is a value derived for a configuration that was not actually implemented.

For Week 2, a different configuration is actually applied to the network, and the feeder currents are again measured and a total circuit load is calculated (Ref#3). From this a second set of scaled individual substation loads are calculated (Ref#6).

Finally a total circuit load for configuration 0 is calculated (Ref#4) using the second set of scaled substation loads (Ref#6). Again, this value is shown in a greyed cell in Table 26 to indicate that it is a value derived for a configuration that was not actually implemented

If load could be considered to be constant between the two time periods, then variance of the ratio Ref#1/Ref#3 from a value of 1 would indicate a change in losses due to altered network configuration. However, load cannot be assumed to be constant with time, and therefore ratio Ref#1/Ref#3 is a function of changed losses due to altered network configuration, and changes in load between periods 1 and 2.

Ratio Ref#1/Ref#4 is related to the change in load, but is also affected by variance between assumed and actual distribution of load along the feeder.

Ratio Ref#2/Ref#3 is similarly related to change in load and variance between assumed and actual distribution of load along the feeder.

It is therefore postulated that the ratio (Ref#1/Ref#4)/(Ref#2/Ref#3) will eliminate the effect of time varying load, but will retain an indication of variance between assumed and actual distribution of feeder load. Therefore a value around 1 for the ratio (Ref#1/Ref#4)/(Ref#2/Ref#3) would indicate no substantial variance between the assumed load distribution of load along the feeder, and the actual distribution of load along the feeder.

Figure 40 is a plot of the ratio for the pre-existing NOP configuration and trials configuration 1 using method 1 to set this configuration. In the chart, the blue trace shows the ratio using our assumed feeder load distribution. From this trace it can be seen that the values varies around 1, indicating no substantial mismatch between assumed load distribution and actual load distribution. Figure 41 Shows and equivalent trace for the OHL Network between the pre-existing nominal configuration 0 and trials configuration 1 set by method 1.

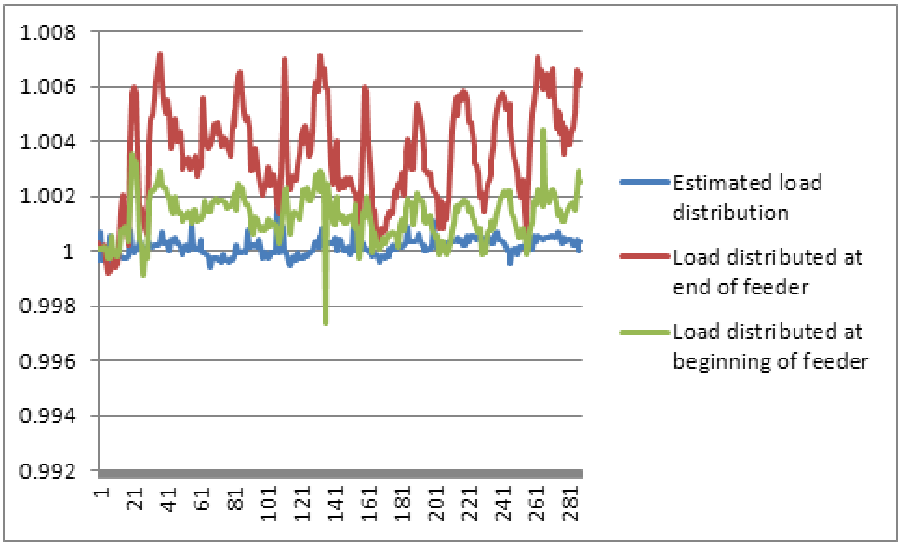


Figure 40 :Cable Network ratio (Ref#1/Ref#4)/(Ref#2/Ref#3) for each half hour slot over trial period

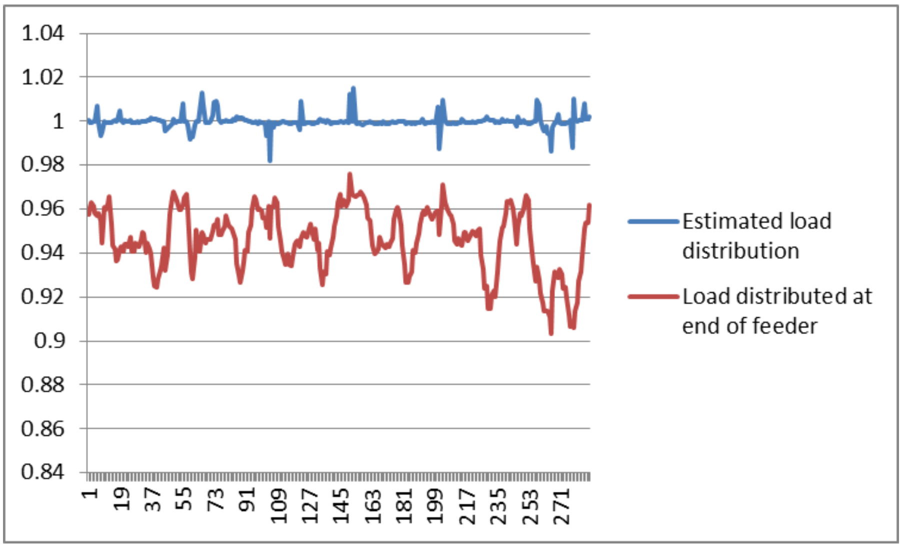


Figure 41 :OHL Network ratio (Ref#1/Ref#4)/(Ref#2/Ref#3) for each half hour slot over trial period

The red trace shows an illustration of the ratio if an alternate load distribution assumption is used (one where the load is substantially biased towards the end of the feeders). This trace does not vary around 1, and shows markedly more variance to load distribution based upon Falcon substation load estimates.

Similarly the green trace, illustrating a further alternate load distribution assumption (where load is biased towards to source end of the feeders), also does not vary about 1, and again shows greater variance in value to the assumed load distribution based upon Falcon substation load estimates.

Based upon the above, it is judged that the assumed load distribution used in this paper's analysis, and based upon Falcon substation load estimates, is a satisfactory basis for subsequent modelling for the purpose of outline benefit assessment.

Figure 42 below provides an overview of the calculations undertaken in the modelling to allow outline benefit assessment.

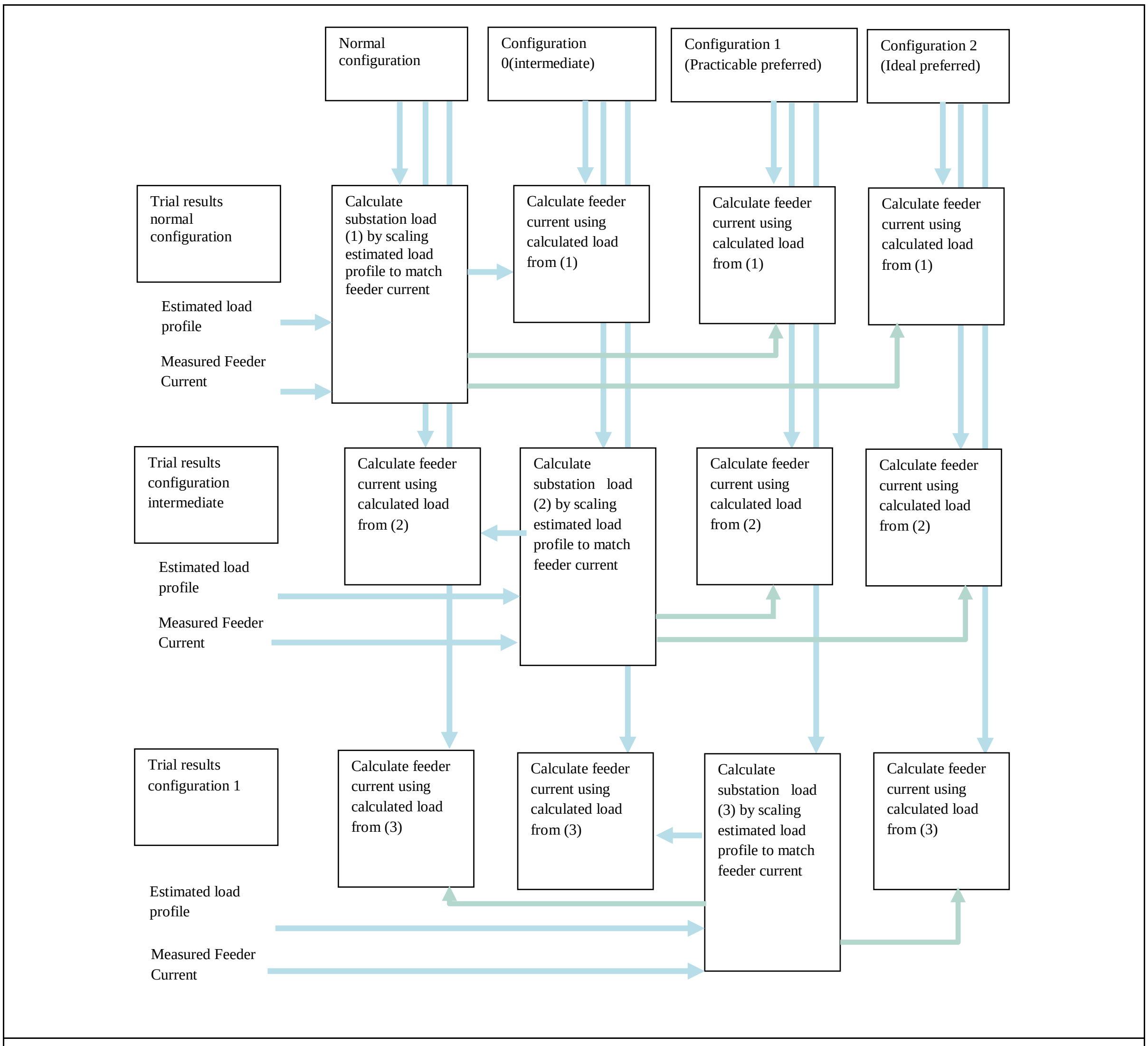


Figure 42: Validation through comparison of recorded and calculated feeder data

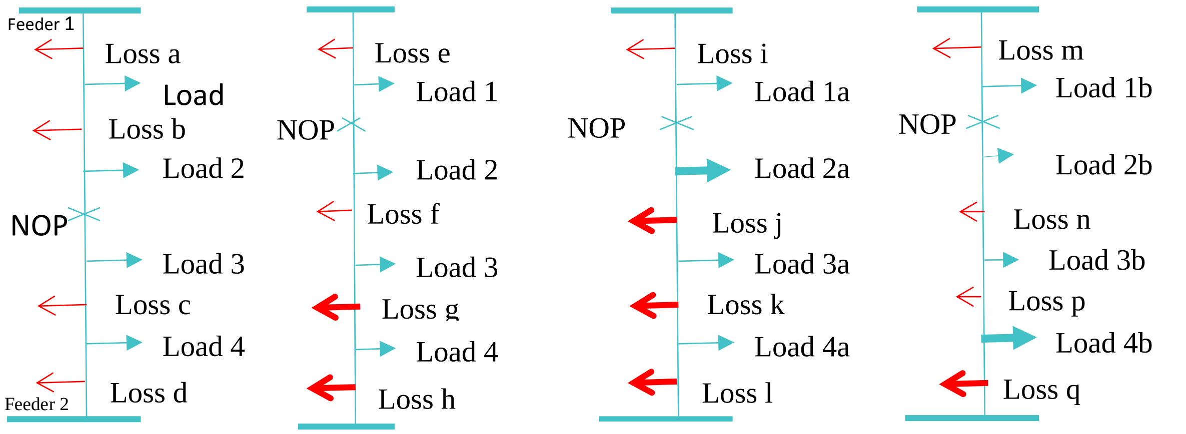
Note: the assertion that the ratio of measured total circuit current to calculated total circuit current (for an alternate NOP configuration of the same circuit) is dependent on variation in the losses arising from the change in circuit configuration is supported by material in Appendix G.

G Effect of feeder load distribution on network losses following changes to network configuration

This appendix provides supporting material to the assertion in Appendix F that the ratio of measured total circuit current to calculated total circuit current (for an alternate NOP configuration of the same circuit) is dependent on variation in the losses arising from the change in circuit configuration.

This concept can be demonstrated with reference to an example shown in Figure 43. In this example a very small circuit is shown, with two feeders, four loads and one open point. In Part A, the total circuit current would be dependent on the individual loads and the losses a-d (assuming that the loads maintain the same cumulative magnitude), and the losses are in turn dependent on:

- the relative size of the loads/distribution of load along the feeder; and
- the position of the open point.



Part A

Part B
Assumption: changed network configuration

Part C
Assumption: Load 2 >> Load 1
This configuration would show an increase in total feeder current compared to Part A.

Part D
Assumption: Load 1 >> Load 2
This configuration would show minimal increase in total feeder current compared to Part A.

Figure 43 : Example showing how results from a poorly conditioned model would be picked up.

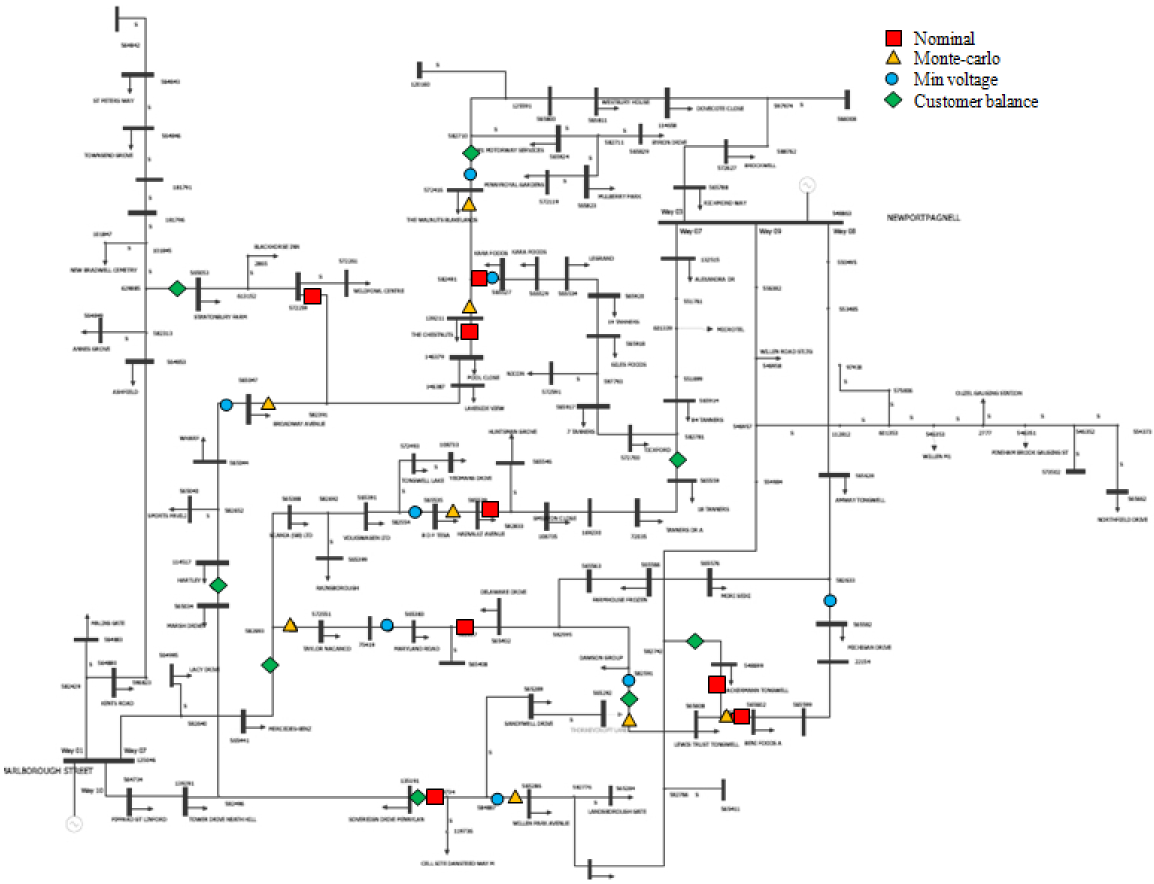
Now consider Part B, if the loads are assumed to be the same magnitude as Part A, the total circuit current would be marginally larger than in Part A due to an increase in circuit losses arising from the configuration change (loss e would be less than loss a, losses g & h would increase by the same decrease is loss a to loss e, and loss b would be approximately equal to loss f).

In Part C, if the individual feeder loads are kept constant to those of Part B, and load 2 is assumed to be much greater proportion of the circuit load than in Part B, then percentage circuit losses will be larger than in Part B.

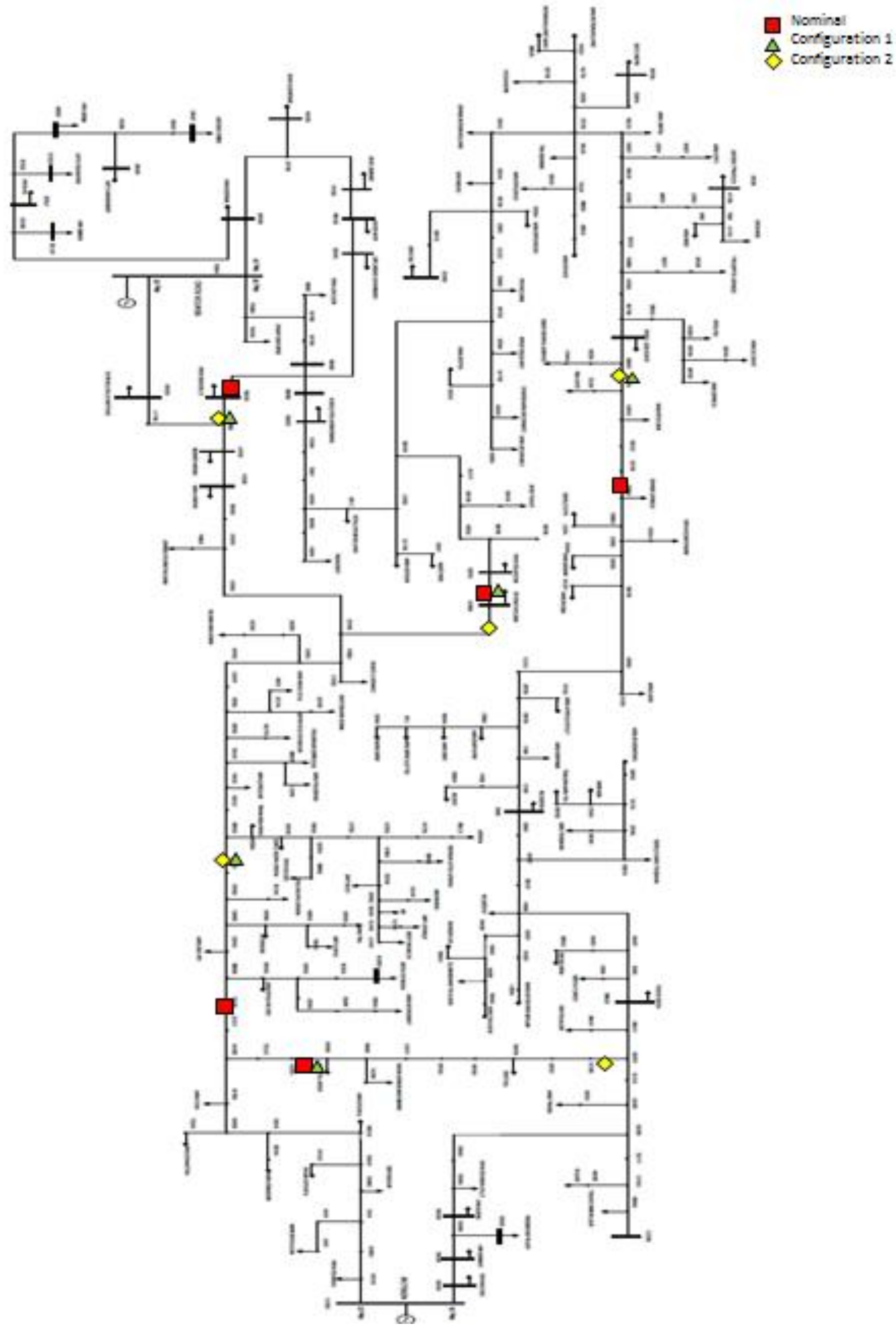
In part D if it is assumed that load 4b is a significantly larger proportion of the circuit load than in Part B and again the individual feeder loads are constant with those of Part B, than percentage circuit losses will be smaller than in Part B.

It can therefore be seen that the distribution of load following a change of NOP configuration is an important factor in assessing the impact of a change in network configuration, and therefore the importance of making appropriate load distribution assumptions.

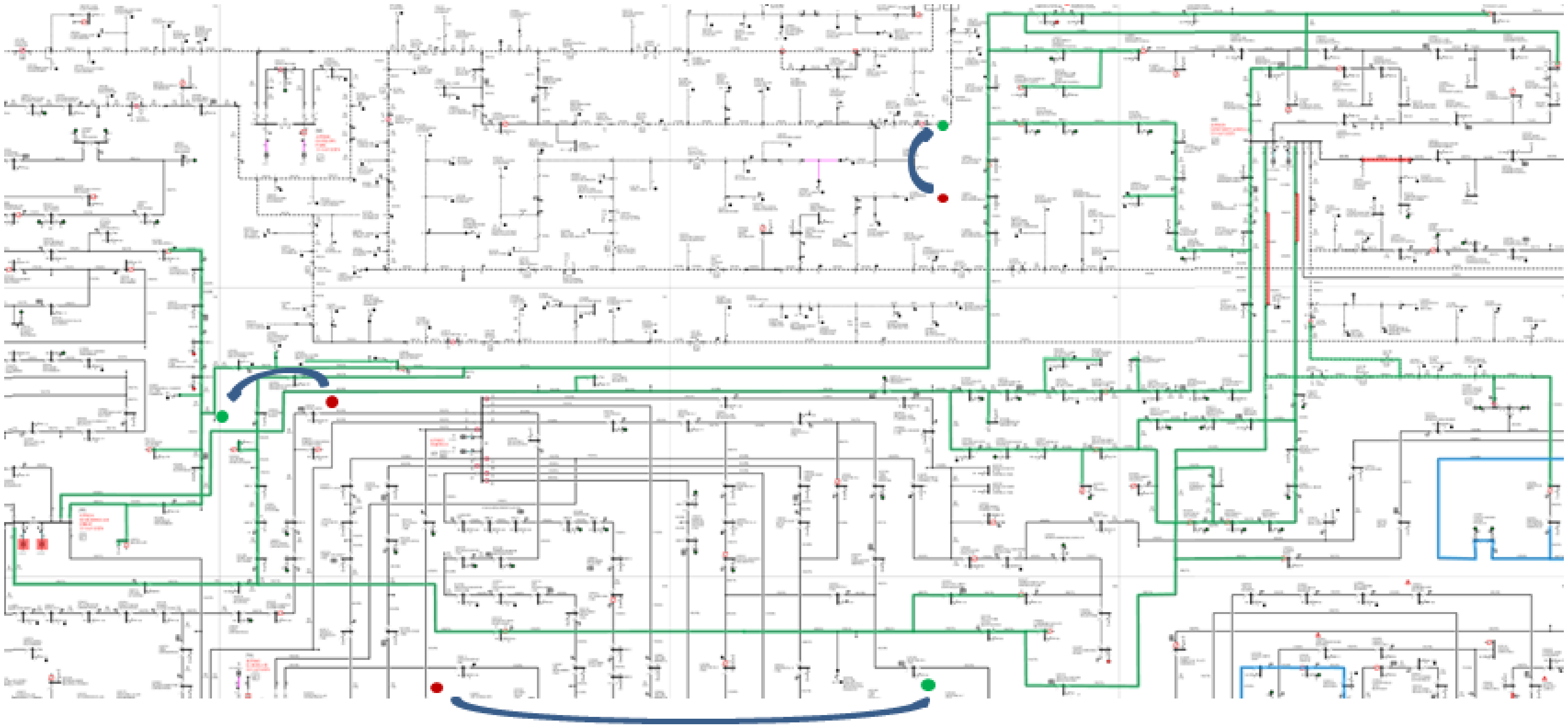
H Method 1 : Monte-Carlo calculation of NOP points



I Method 1 : OHL Trial Network NOP location

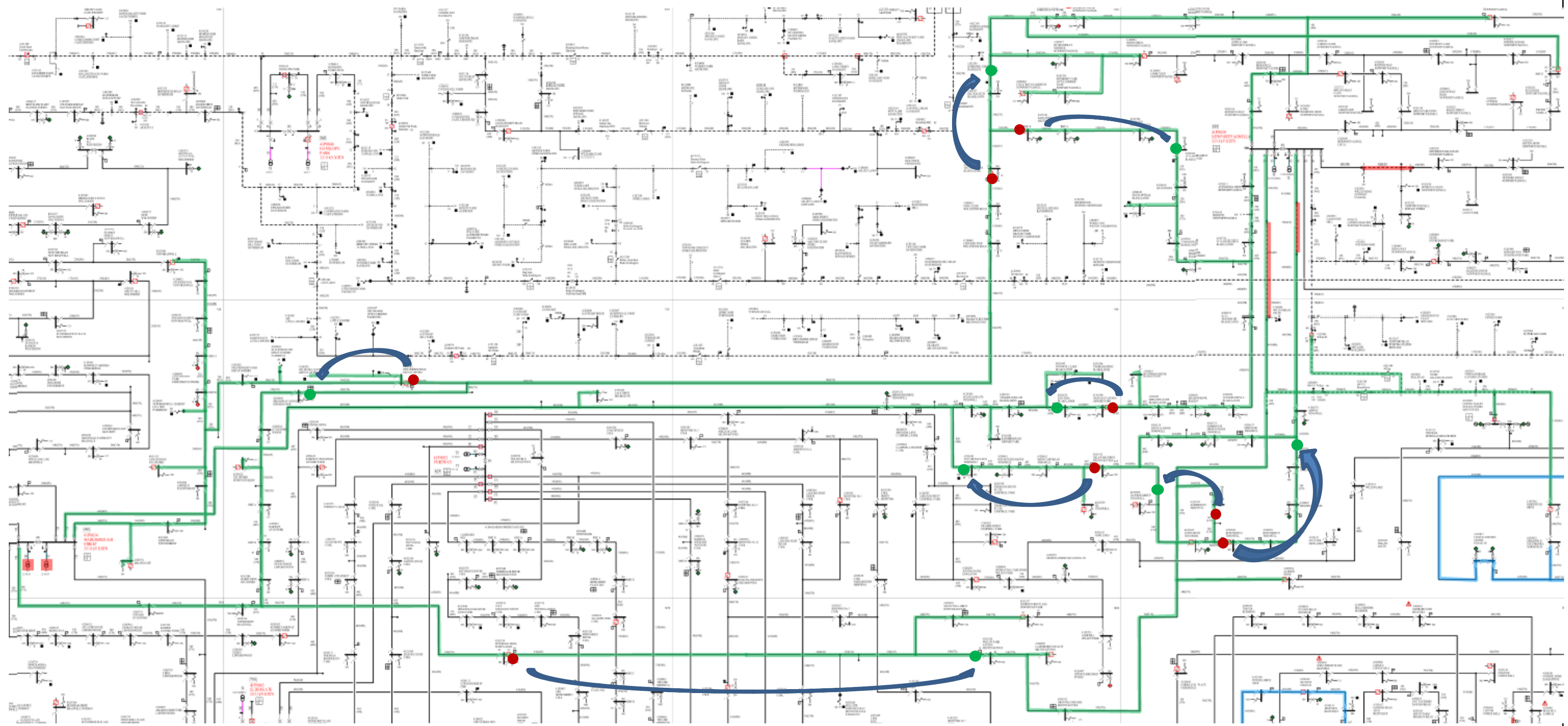


J Method 1 : Cable trial HV Diagrams



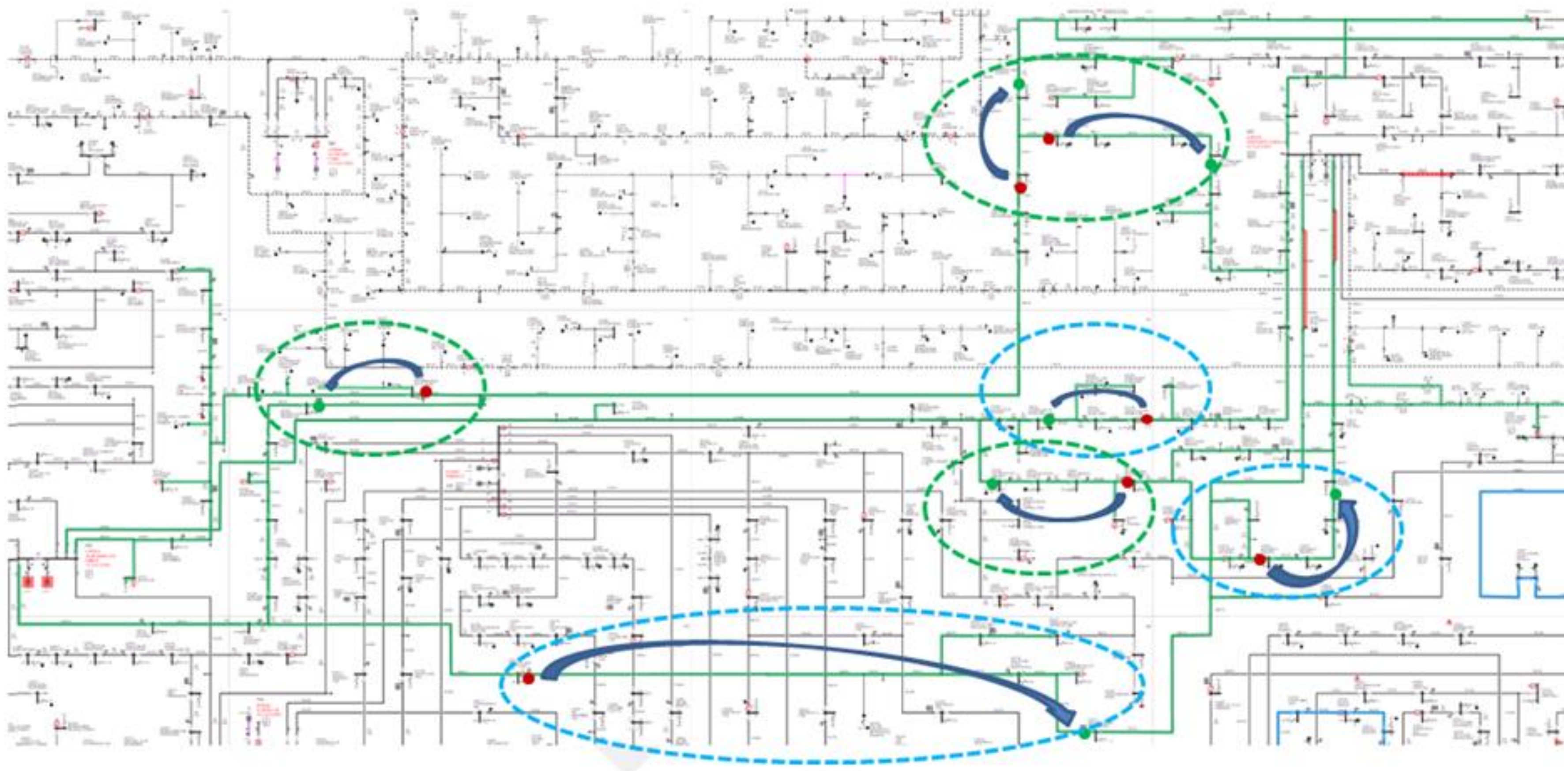
Key: red dot is pre-existing NOP; green dot is identified improved NOP

Figure 44: HV diagram showing Intermediate NOP configuration applied during 22-29th May 2014



Key: red dot is pre-existing NOP; green dot is identified improved NOP

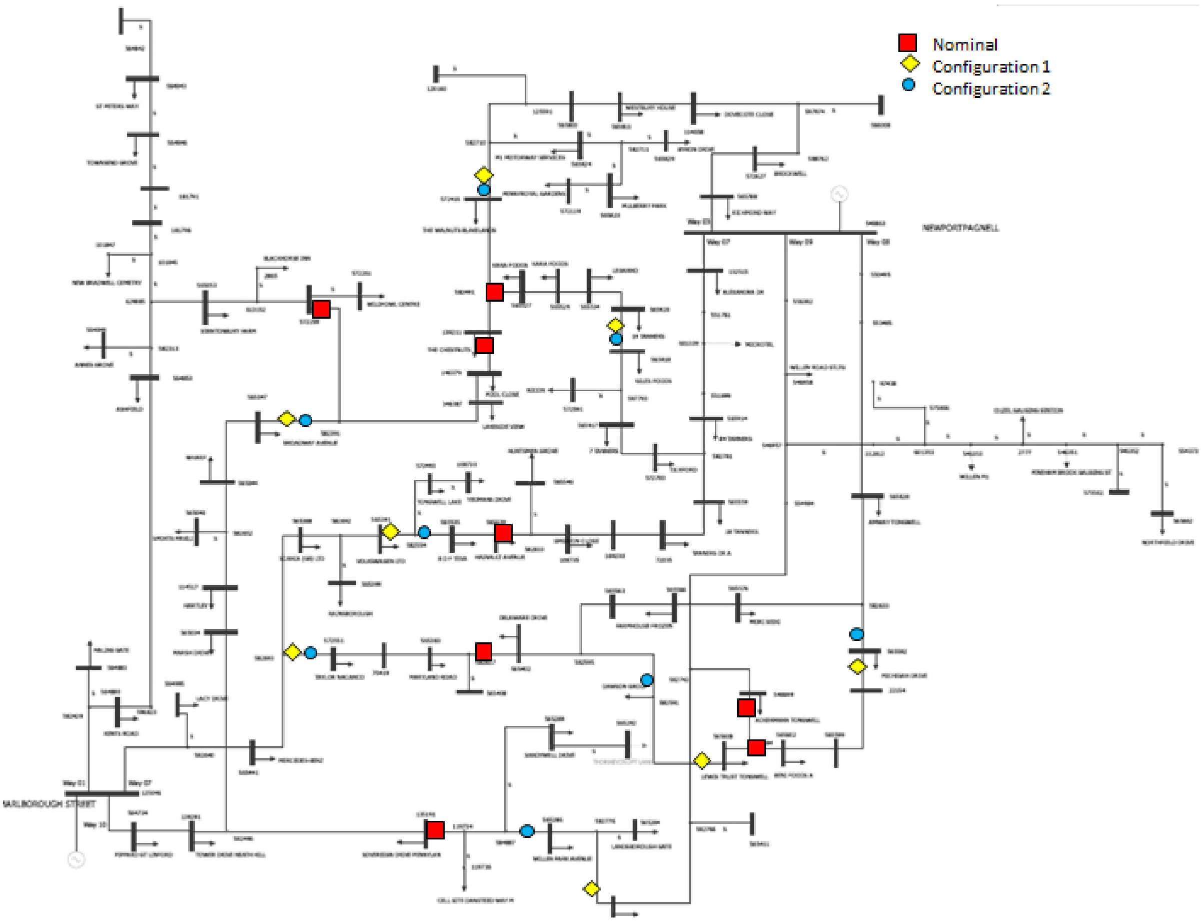
Figure 45: HV diagram showing Configuration 2 – ideal preferred configuration



Key: red dot is pre-existing NOP; green dot is identified improved NOP.

Figure 46: HV diagram showing **configuration 1 - practicable preferred configuration applied during 17-24 June 2014**

K Method 1 : Cable Trial Network NOP location



Cable Trial Network showing location of calculated open points

L Method 1 : OHL Seasonal Switching Pattern

The following tables show the recommended NOP location over the ten sample days using Method 1.

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	Move NOP to other side of load
NOP4	Swanbourne Station	Mursley West	Quantify the changes in load through the day and assess if it is worth undertaking any switching
NOP5	Newton Longville	Variable through the day between Brookfield and Newton Longville	Quantify the changes in load through the day and assess if it is worth undertaking any switching

Table 27 : Winter Sunday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	Move NOP to other side of load
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Newton Longville	Move NOP to other side of load

Table 28 : Spring Sunday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	Quantify the changes in load through the day and assess if it is worth undertaking any switching
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Newton Longville	Move NOP to other side of load

Table 29 : Summer Sunday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	move NOP to other side of load
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Newton Longville	Move NOP to other side of load

Table 30 : High Summer Sunday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	move NOP to other side of load
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Newton Longville	Quantify the changes in load through the day and assess if it is worth undertaking any switching

Table 31 : Autumn Sunday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	Move NOP to other side of load
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Variable through the day between Brookfield and Newton Longville	Quantify the changes in load through the day and assess if it is worth undertaking any switching

Table 32 : Winter Wednesday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	Move NOP to other side of load
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Newton Longville	Move NOP to other side of load

Table 33 : Spring Wednesday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	Quantify the changes in load through the day and assess if it is worth undertaking any switching
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Newton Longville	Move NOP to other side of load

Table 34 : Summer Wednesday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	Move NOP to other side of load
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Newton Longville	Move NOP to other side of load

Table 35 : High Summer Wednesday – summary of switching schedule

NOP	Pre-existing NOP	Preferred NOP	Comments
NOP1	Wing Road	Dove Street	Move NOP
NOP2	Swanbourne	Not switchable	Retain
NOP3	St Georges Road	St Georges Road	Move NOP to other side of load
NOP4	Swanbourne Station	Mursley West	Move the NOP
NOP5	Newton Longville	Newton Longville	Move NOP to other side of load

Table 36 : Autumn Wednesday – summary of switching schedule

M Method 1 : Cable Seasonal Switching Pattern

- Delaware Drive
  - no across-season variation, though a significant change from the existing NOP, moves to Taylor Nacanco.

Conclusion: **insensitive to seasonal change, within-week change and daily change – recommend NOP moves statically to Taylor Nacanco**

- Sovereign Drive
  - no evidence suggesting seasonal variation for weekdays, though NOP moves to Willen Park;
  - some suggestion that there is daily variation at weekends (for 3 seasons) whilst no variation with days for two of the seasons (Winter and Summer)

Conclusion: **Largely insensitive to seasonal and within-week changes, some potential for within-day changes at weekends in certain seasons - recommend NOP moves statically to Willen Park**

- Chestnuts
  - 4 out of five seasons show some daily variation during weekdays, and these differences change with season
  - No evidence suggesting seasonal variation for weekends (though there is a shift to Walnuts from current NOP)

Conclusion: **Largely insensitive to seasonal and within-week changes, possibly some potential for within-day changes on weekdays in certain seasons - recommend NOP moves statically to Walnuts**

- Kara Foods – **potentially insensitive to seasonal change, with sensitivity to in-week and within-day variation**
  - 3 seasons show some daily variation in preferred NOP location for weekends (variation around which side of the Kara Foods load the NOP should be), though this changes from season to season; 2 seasons suggest static NOP through the day (with NOP located the other side of Kara foods from the pre-existing NOP;
  - All five profile seasons show in-day variation in the preferred NOP for weekdays, and the pattern of changes is different between the seasons, possibly suggesting sensitivity to Kara foods load (rather than wider seasonal load change)

Conclusion - **potentially insensitive to seasonal change, with sensitivity to in-week and within-day variation – recommendation: retain Kara Foods, though change(s) to this open point could be anticipated, but more analysis is required before a specific recommendation can be made**

- Wolverton Road

  - no across season variation for weekends or weekdays, though a significant change from the existing NOP, moves to Broadway Avenue

Conclusion: **insensitive to seasonal change, within-week change and daily change – recommend NOP moves statically to Broadway Avenue**

- Hainault Avenue
  - All five profile seasons show in-day variation in the preferred NOP for weekdays, with a general movement of preferred NOP towards Volkswagen during day hours
  - All five profile seasons show in-day variation in the preferred NOP for weekdays, with a general movement of preferred NOP towards Volkswagen towards the end of Sundays

Conclusion: **probably insensitive to seasonal change, but sensitive to within-week and daily change – recommendation: retain Hainault Avenue NOP, though change(s) to this open point could be anticipated, but more analysis is required before a specific recommendation can be made**

- Ackerman (closely related to Beni Foods) –note: difficult interpretation in this area because the model identifies a number of electrically connected nodes with no load connected, and no switches (now)
  - Across season weekdays clearly show that NOP should be retained at Ackerman, with no in-day variation.
  - For weekends, recommended interpretation is that Ackerman should be retained as the open point, within days and across seasons

Conclusion & recommendation – retain Ackerman as static NOP

- Beni Foods (closely related to Ackerman)
  - For weekends, recommended interpretation is that Beni Foods should be retained as the open point, within days and across seasons
  - For weekdays, evidence shows some movement in the preferred NOP towards Michigan Drive throughout daytime hours

Conclusion & recommendation – **retain Beni Foods NOP, though change(s) to this open point could be anticipated for weekdays, but more analysis is required before a specific recommendation can be made**

N Method 2 : Cable NOP location determination

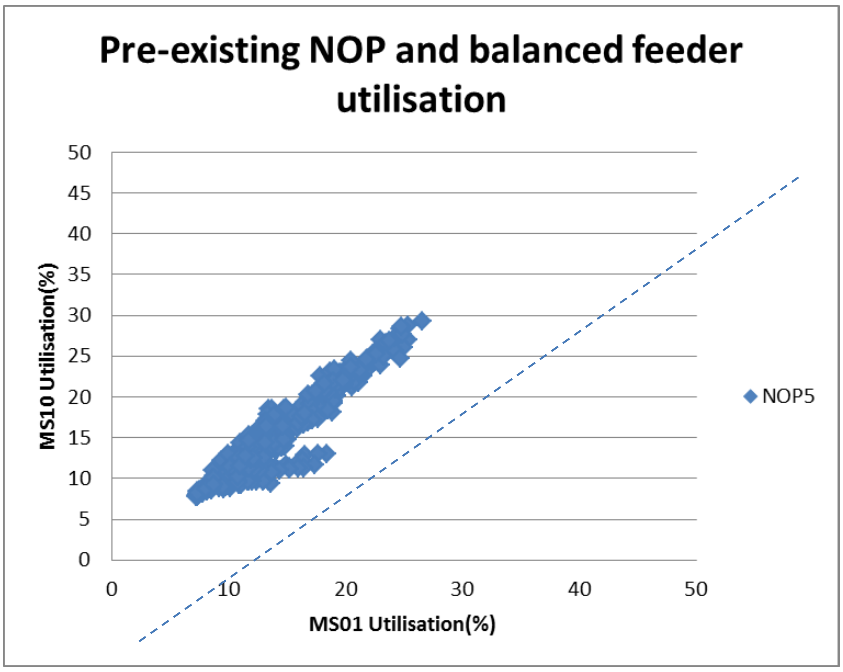


Figure 47: Feeder utilisation with pre-existing NOP between MS10 and MS01 (No.5 Wolverton Rd)

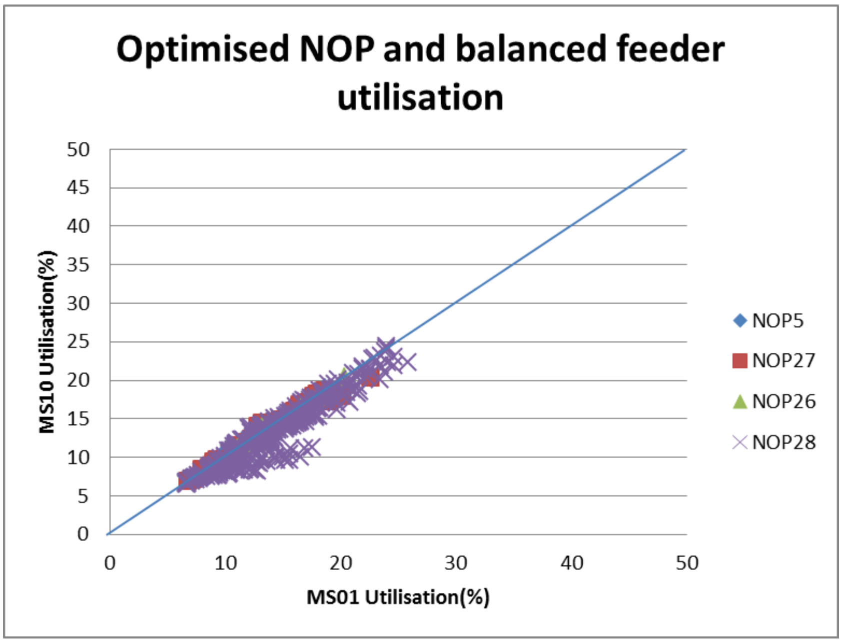


Figure 48: Feeder utilisation with optimised NOP between MS10 and MS01 (No.5 Wolverton Rd)

Proportion of time at each NOP: NOP5-4.8%; NOP26-3.5%; NOP27-8.1% ; NOP28-83.5%

Level of balance between MS01 and MS10 is slightly improved by NOP relocation.

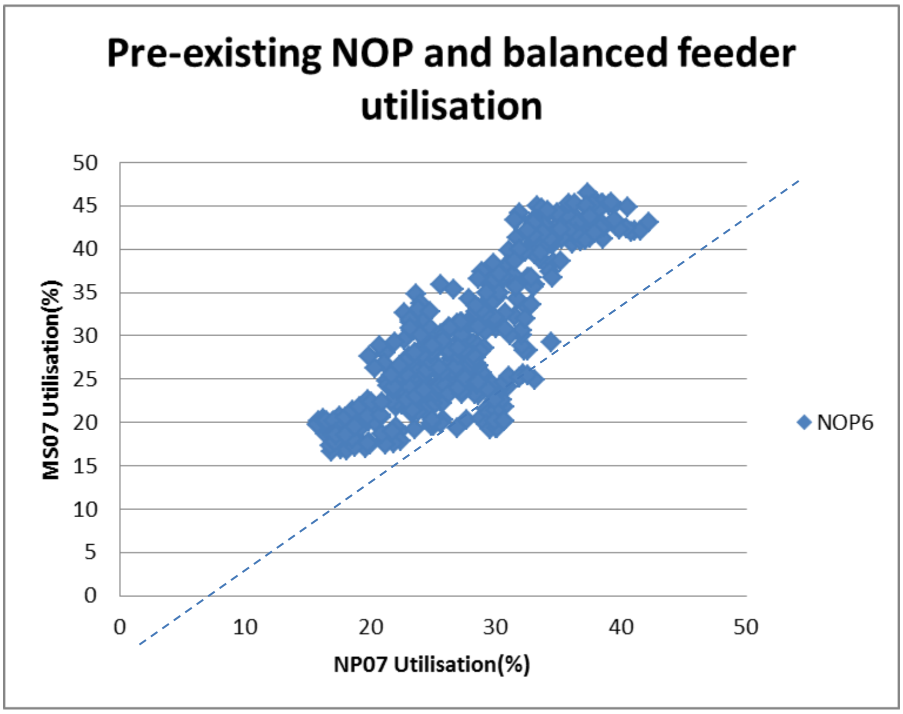


Figure 49: Feeder utilisation with pre-existing NOP between MS07 and NP07 (No.6 Hainault)

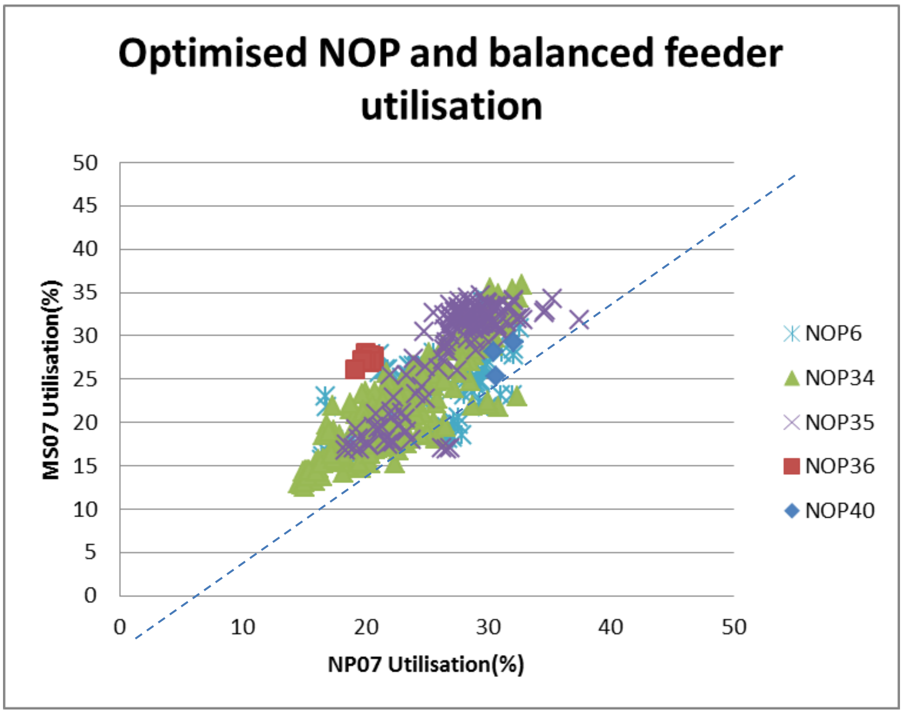


Figure 50 Feeder utilisation with optimised NOP between MS07 and NP07 (No. Hainault)

Proportion of time at each NOP: NOP6-21.3%; NOP34-48.3%; NOP35-27.5% ; NOP36-2.3%; NOP40-0.6%

Level of balance between NP07 and MS07 is improved by NOP relocation.

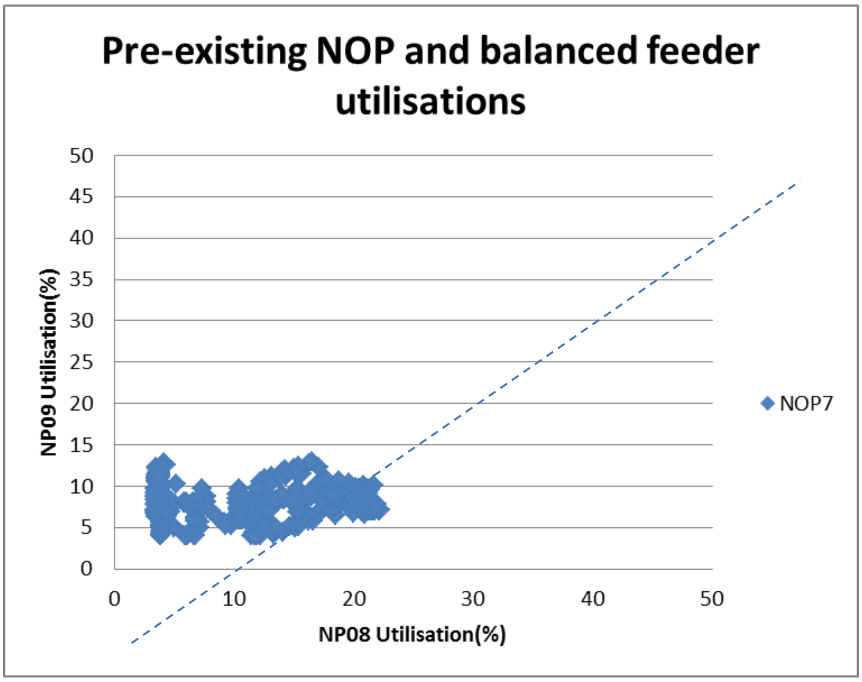


Figure 51: Feeder utilisation with pre-existing NOP between NP09 and NP08 (No. 7 Ackerman)

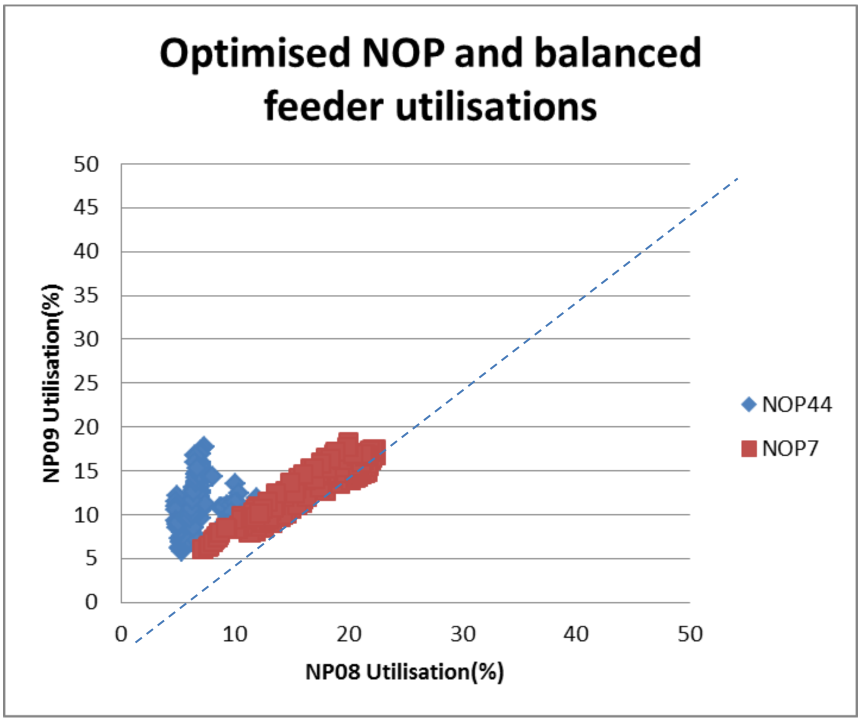


Figure 52: Feeder utilisation with optimised NOP between NP09 and NP08 (No. 7 Ackerman)

Proportion of time at each NOP: NOP7-53.5%; NOP44-46.5%

Level of balance between NP08 and NP09 is slightly worsened by NOP relocation.

O Method 1: OHL feeder utilisation results

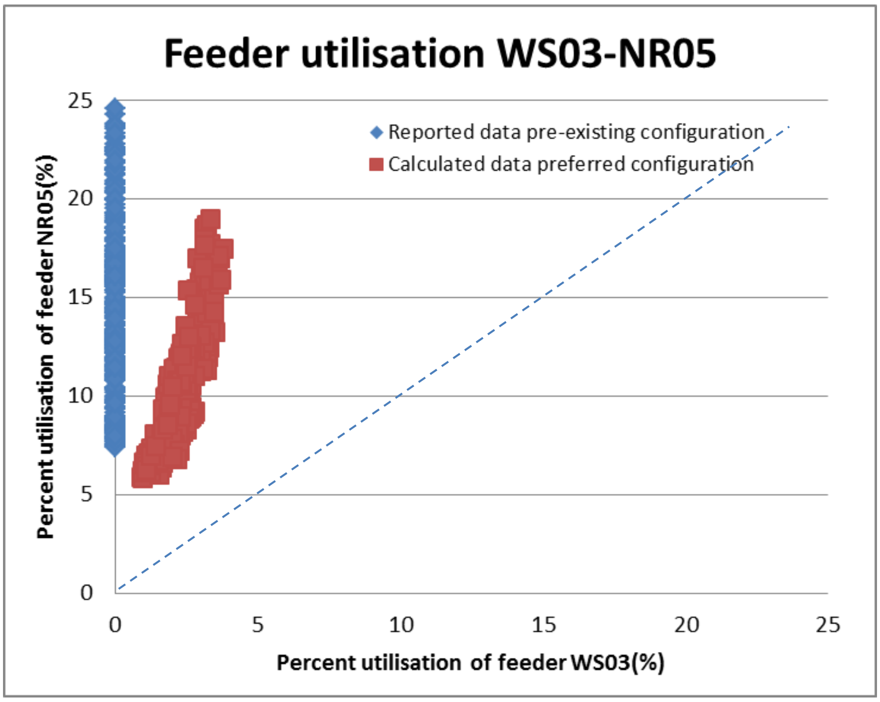


Figure 53: Measured and estimated feeder utilisation of WS03 and NR05 over week 1

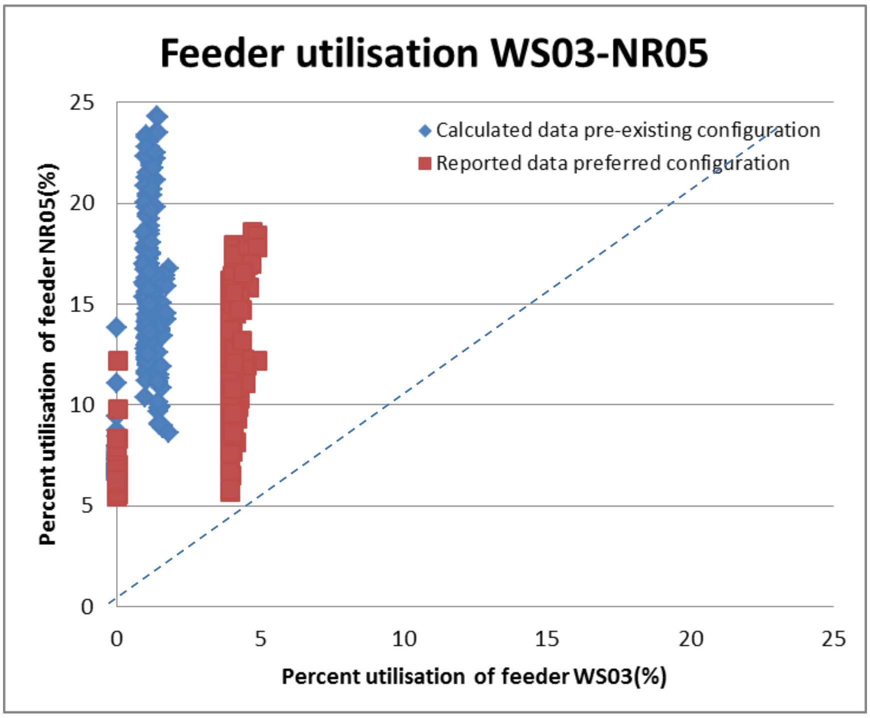


Figure 54: Measured and estimated feeder utilisation of WS03 and NR05 over week 2

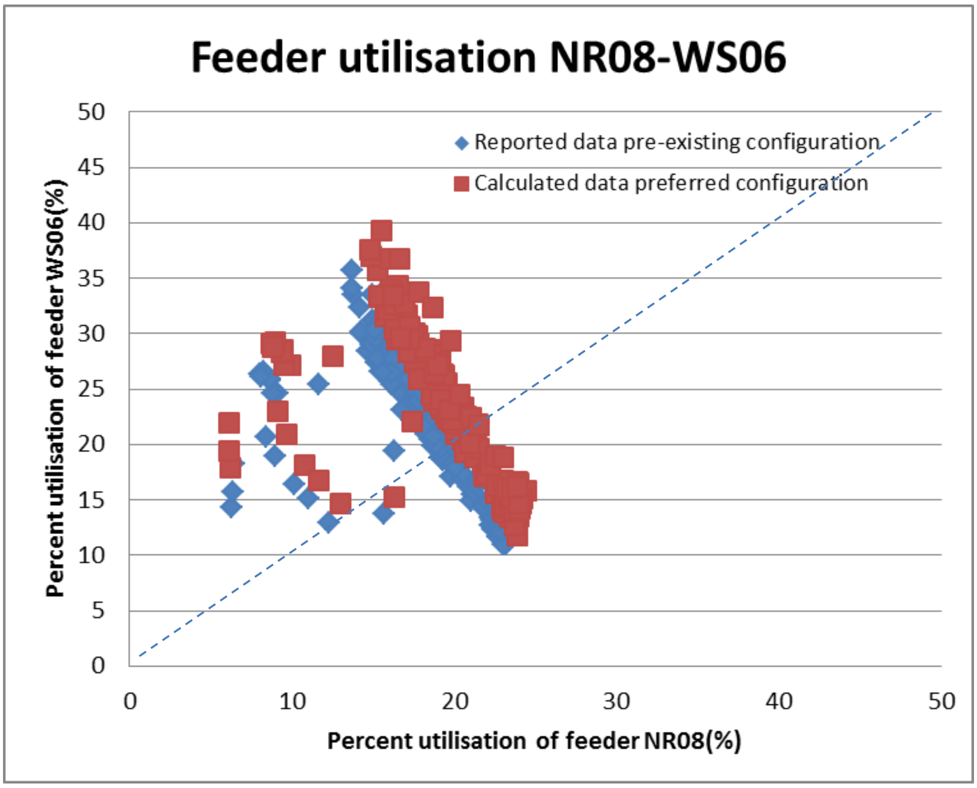


Figure 55: Measured and estimated feeder utilisation of WS06 and NR08 over week 1

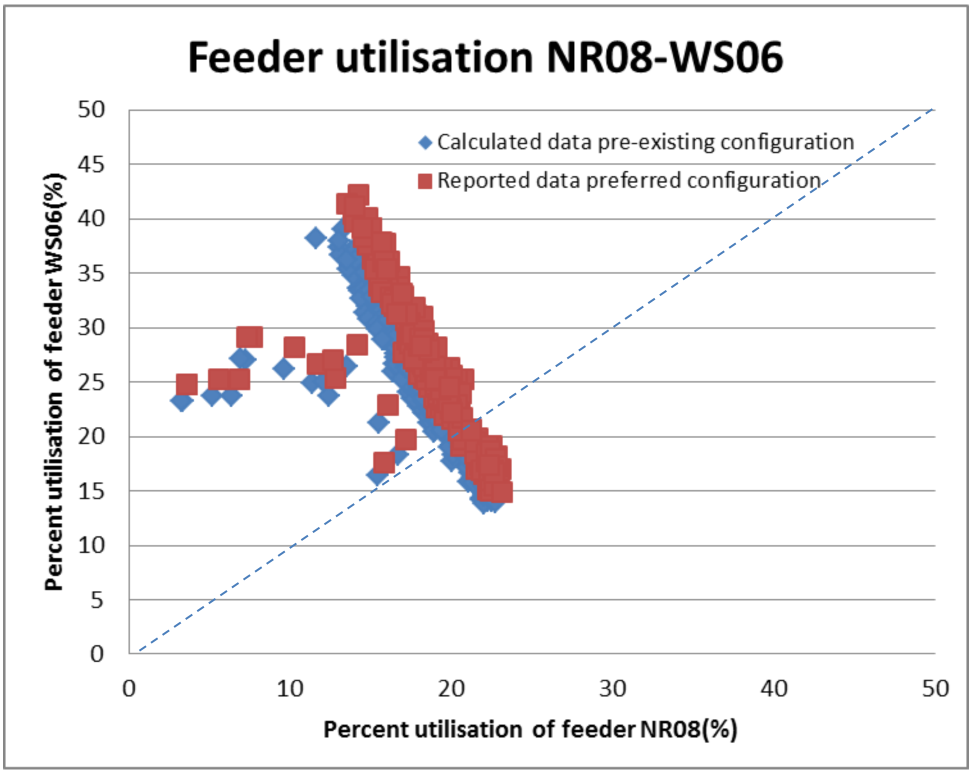


Figure 56: Measured and estimated feeder utilisation of WS06 and NR08 over week 2

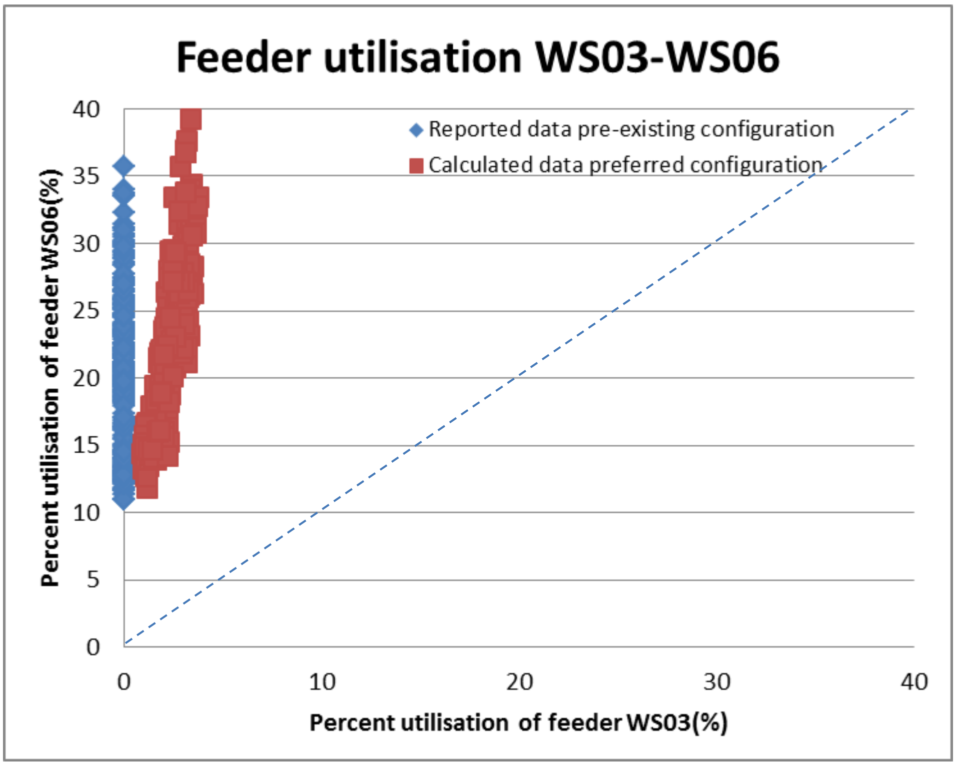


Figure 57 : Measured and estimated feeder utilisation of WS03 and WS06 over week 1

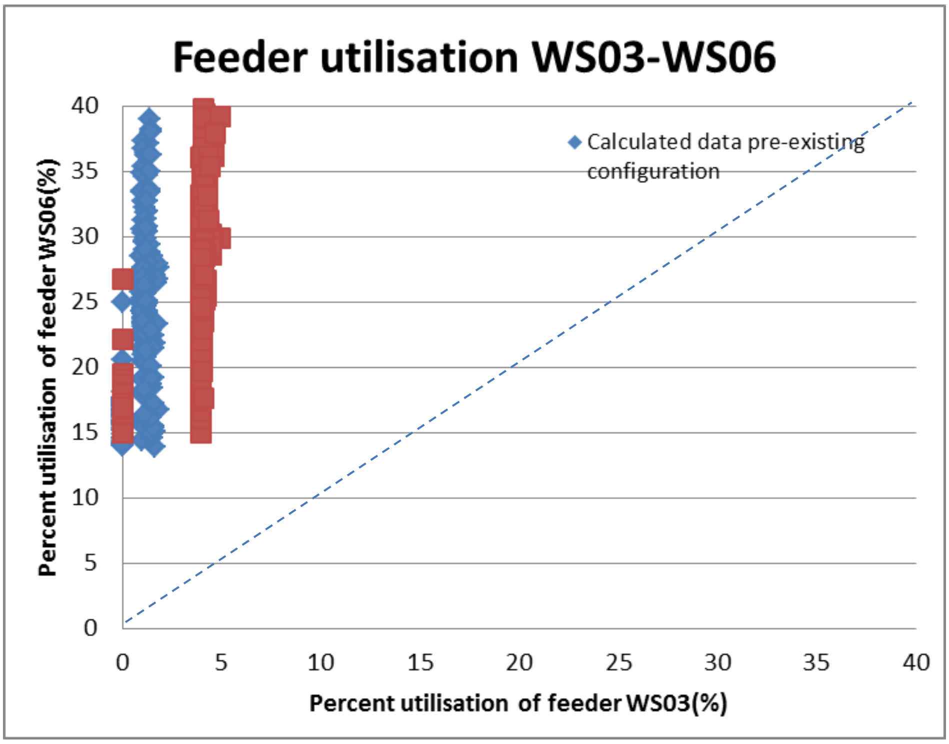


Figure 58 : Measured and estimated feeder utilisation of WS03 and WS06 over week 2

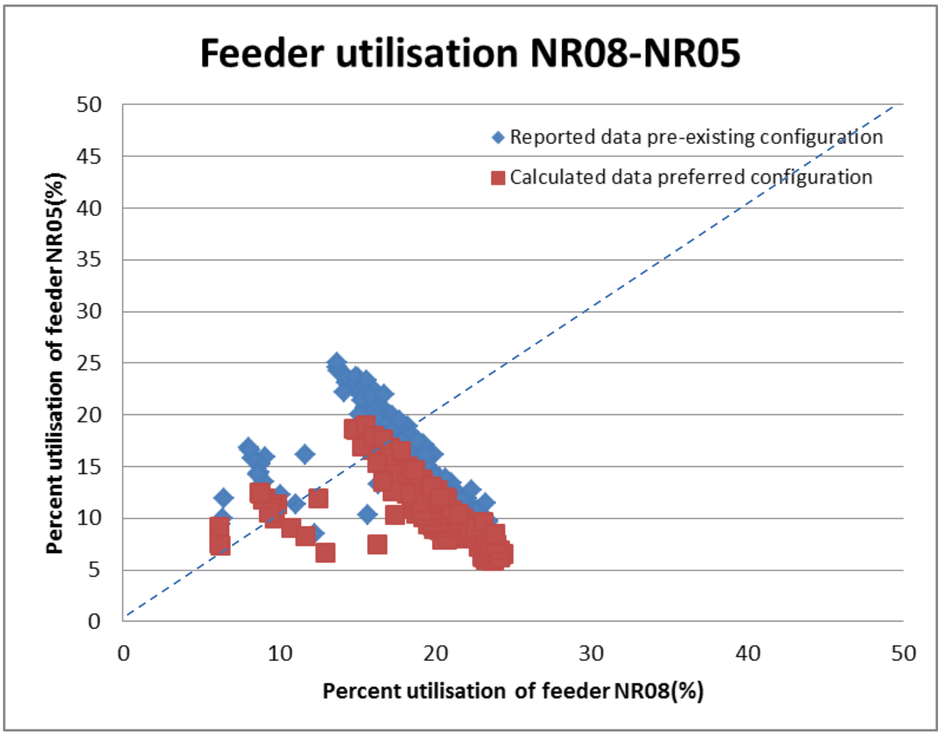


Figure 59 : Measured and estimated feeder utilisation of NR08 and NR05 over week 1

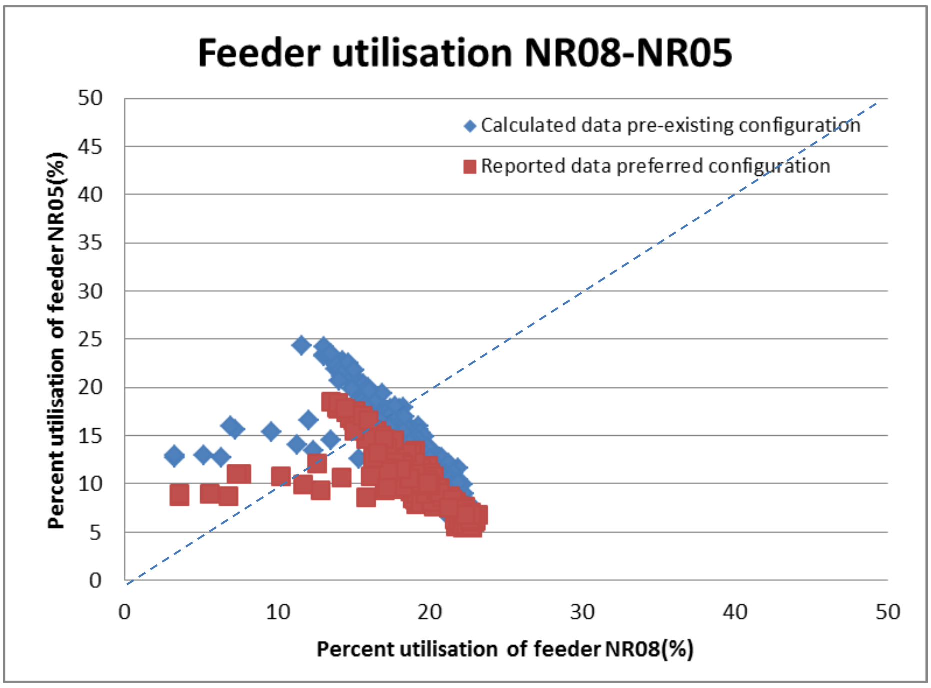


Figure 60 : Measured and estimated feeder utilisation of NR08 and NR05 over week 2

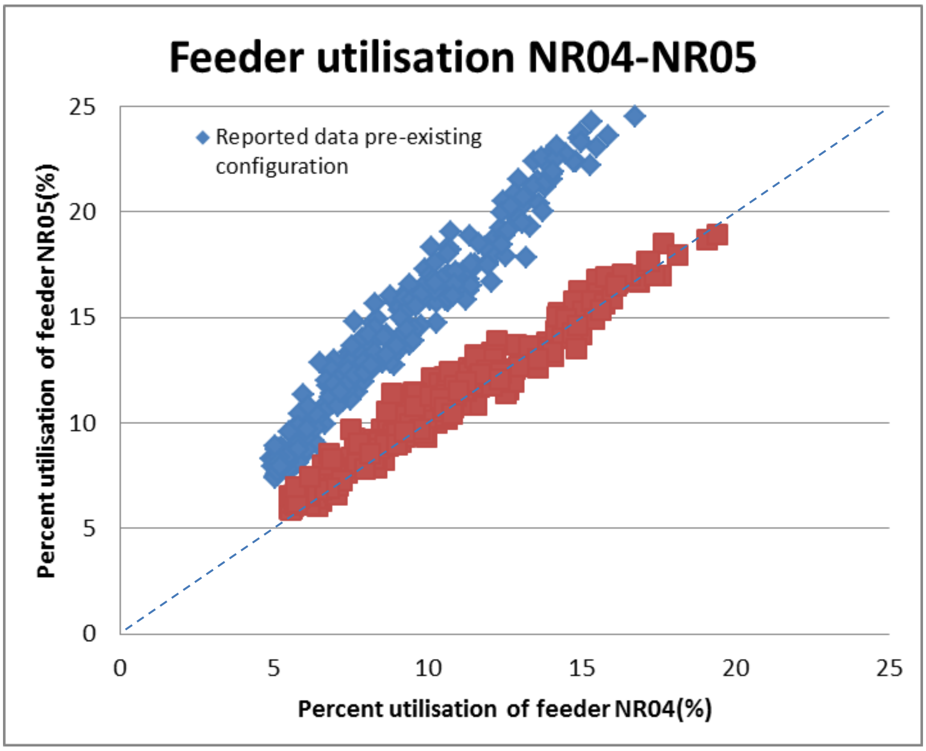


Figure 61 : Measured and estimated feeder utilisation of NR04 and NR05 over week 1

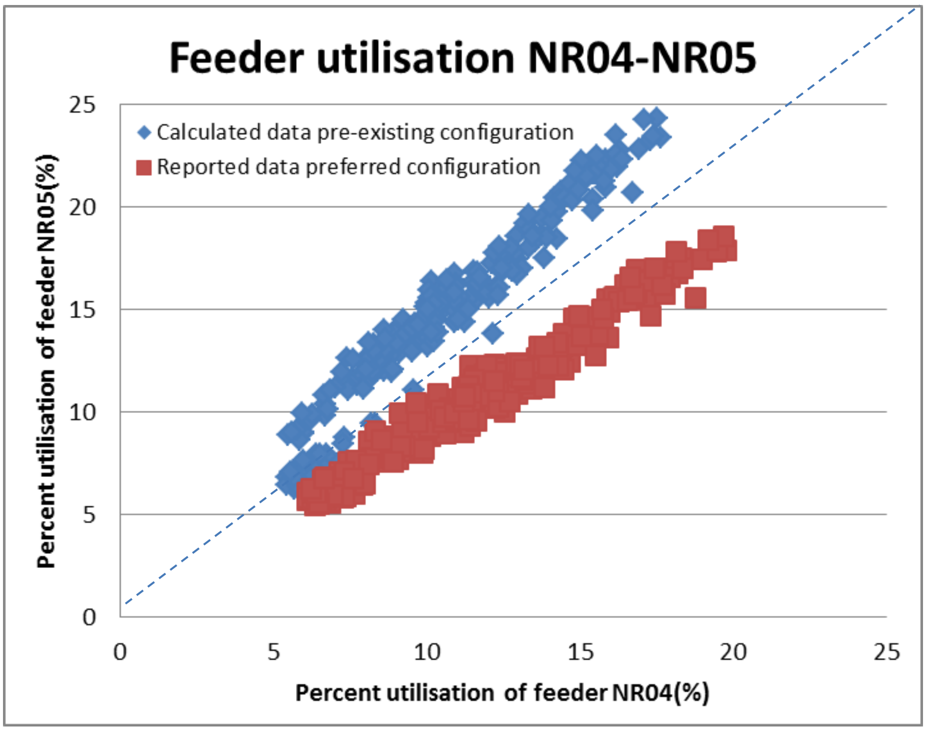


Figure 62 : Measured and estimated feeder utilisation of NR04 and NR05 over week 2

P Method 1: Cable feeder utilisation results

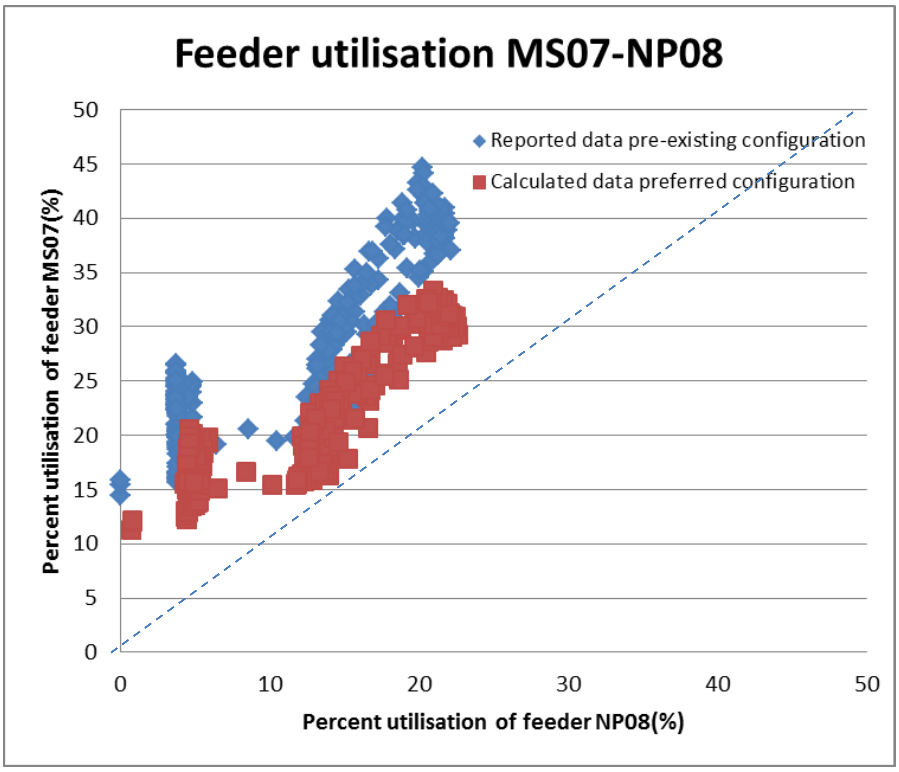


Figure 63: Measured and estimated feeder utilisation of MS07 and NP08 over week 1

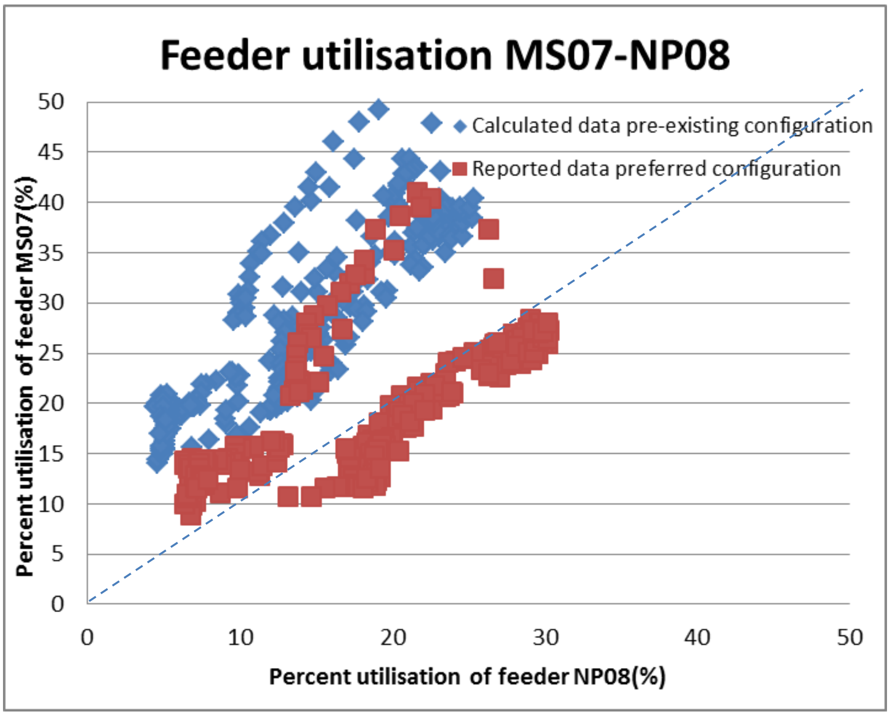


Figure 64: Measured and estimated feeder utilisation of MS07 and NP08 over week 2

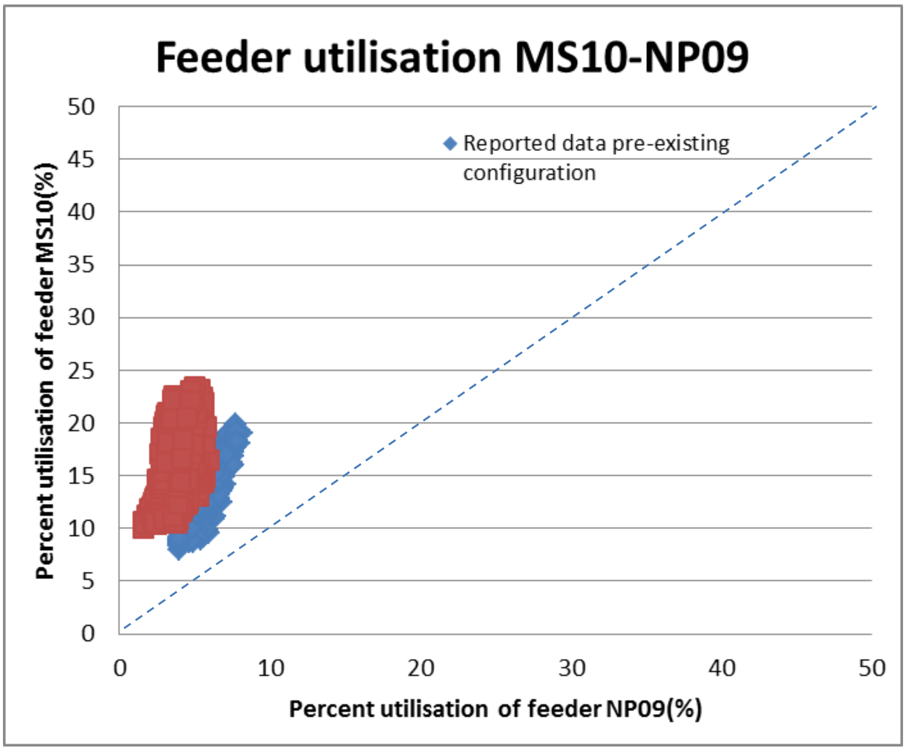


Figure 65: Measured and estimated feeder utilisation of MS10 and NP09 over week 1

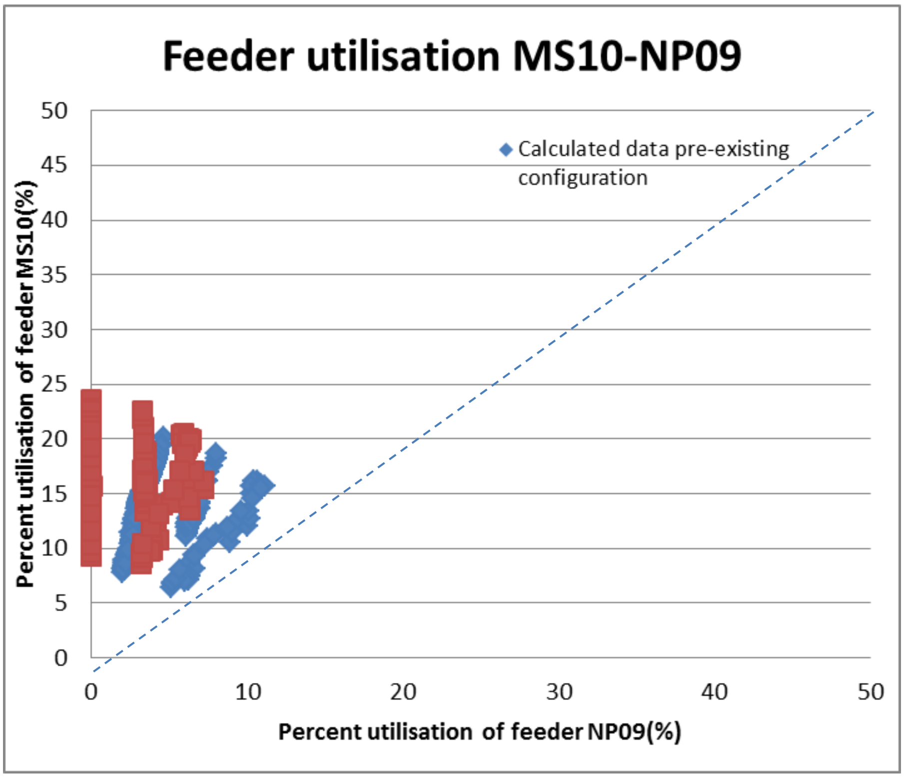


Figure 66: Measured and estimated feeder utilisation of MS10 and NP09 over week 2

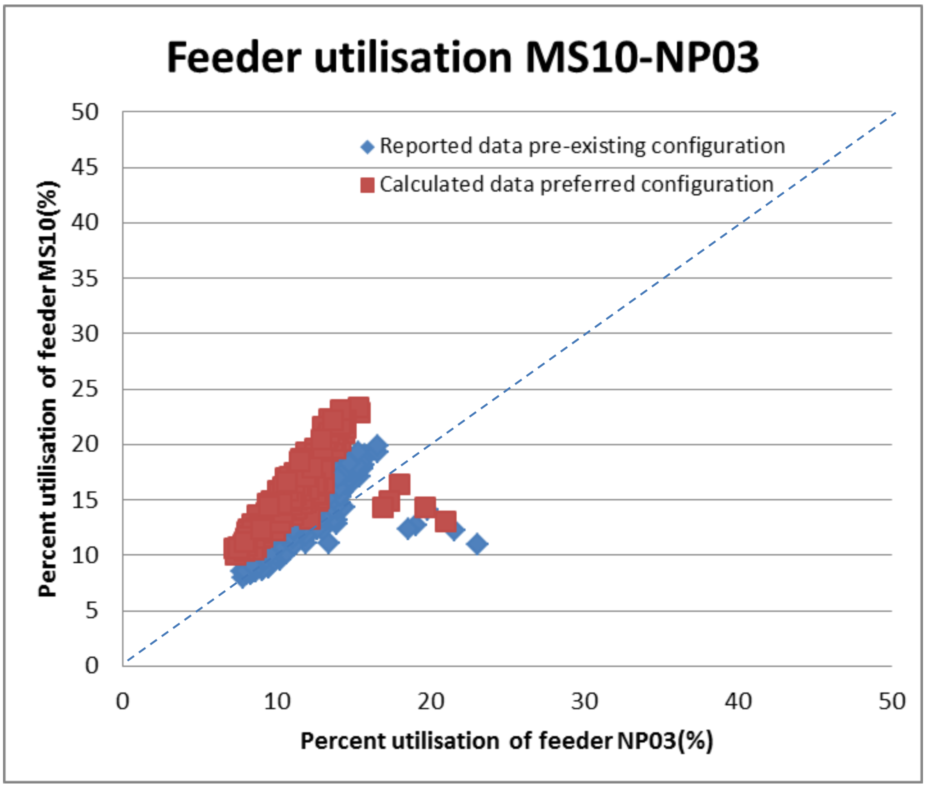


Figure 67 : Measured and estimated feeder utilisation of MS10 and NP03 over week 1

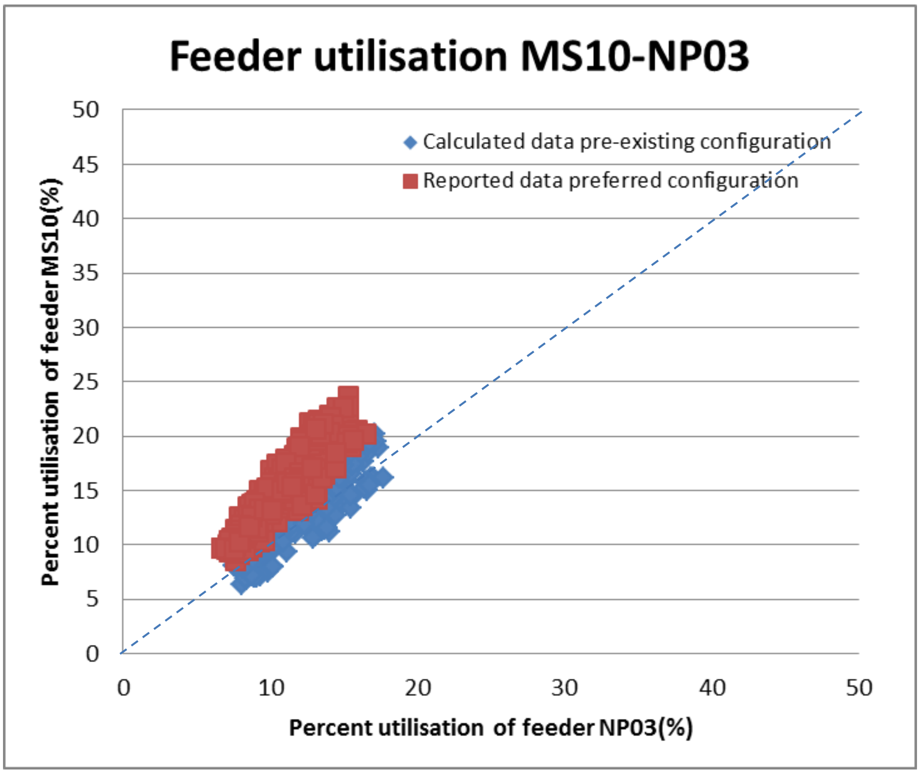


Figure 68 : Measured and estimated feeder utilisation of MS10 and NP09 over week 2

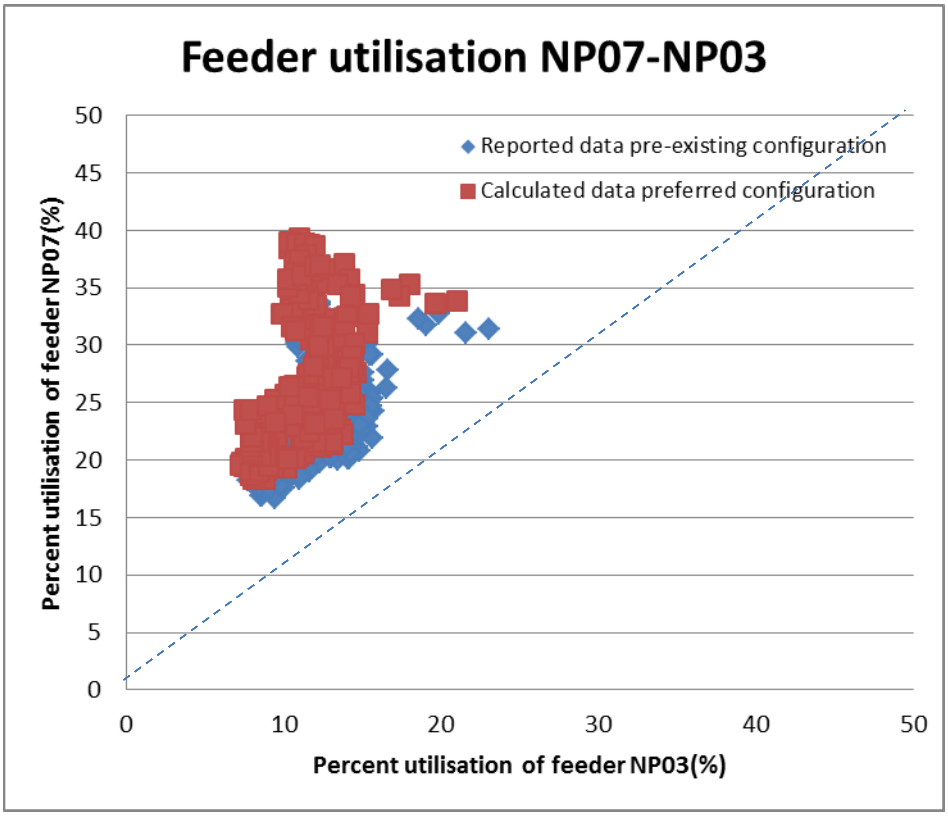


Figure 69 : Measured and estimated feeder utilisation of NP07 and NP03 over week 1

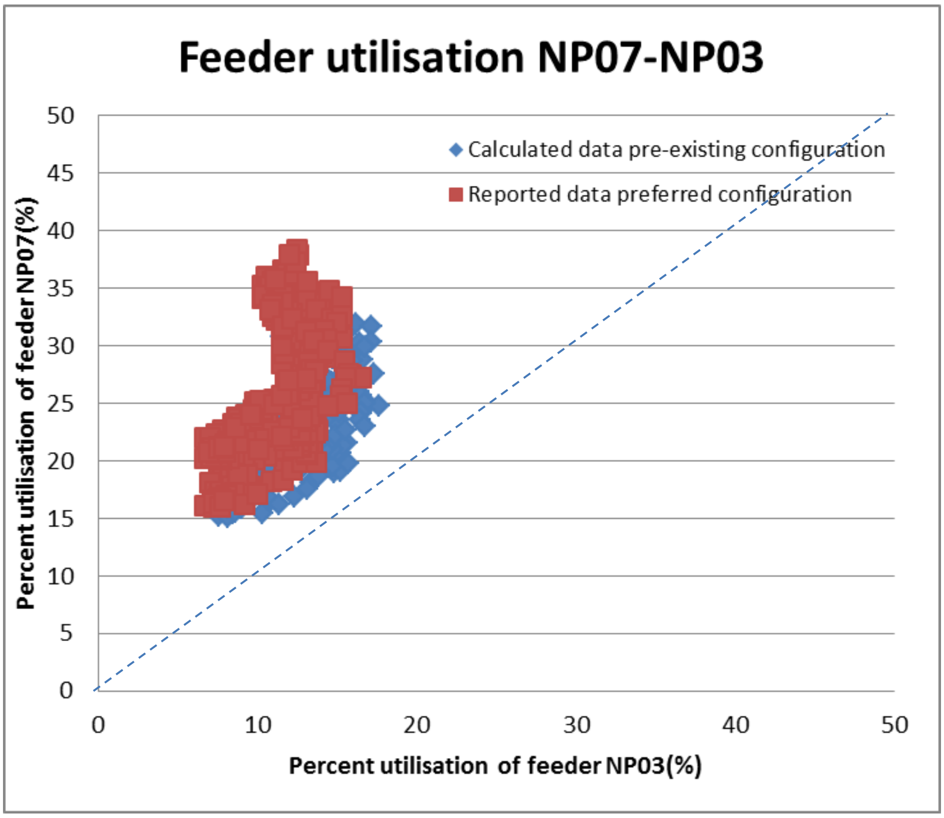


Figure 70 : Measured and estimated feeder utilisation of NP07 and NP03 over week 2

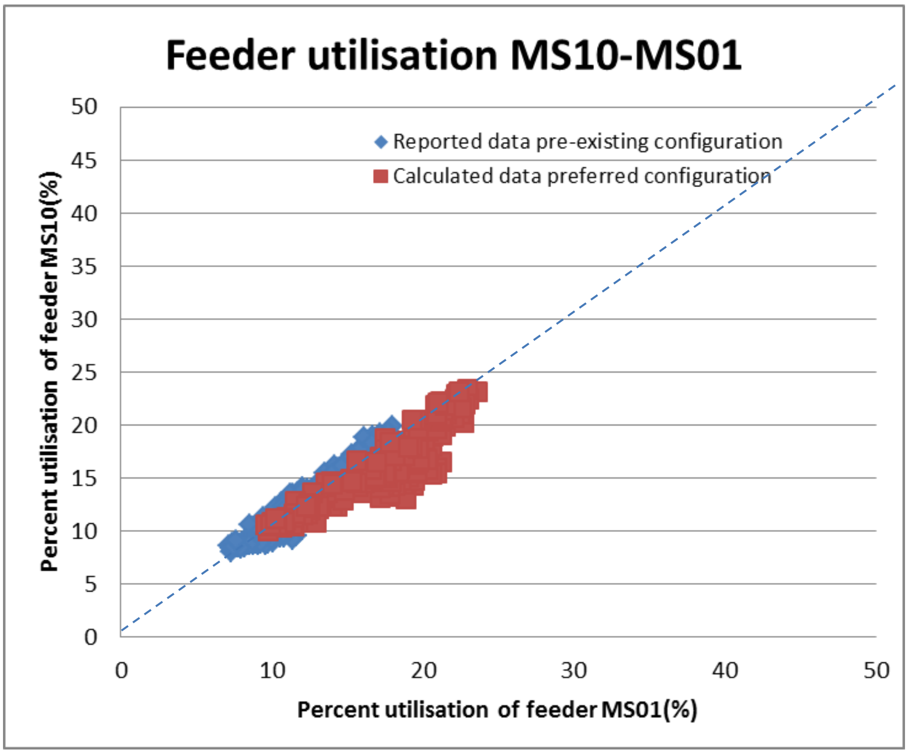


Figure 71 : Measured and estimated feeder utilisation of MS10 and MS01 over week 1

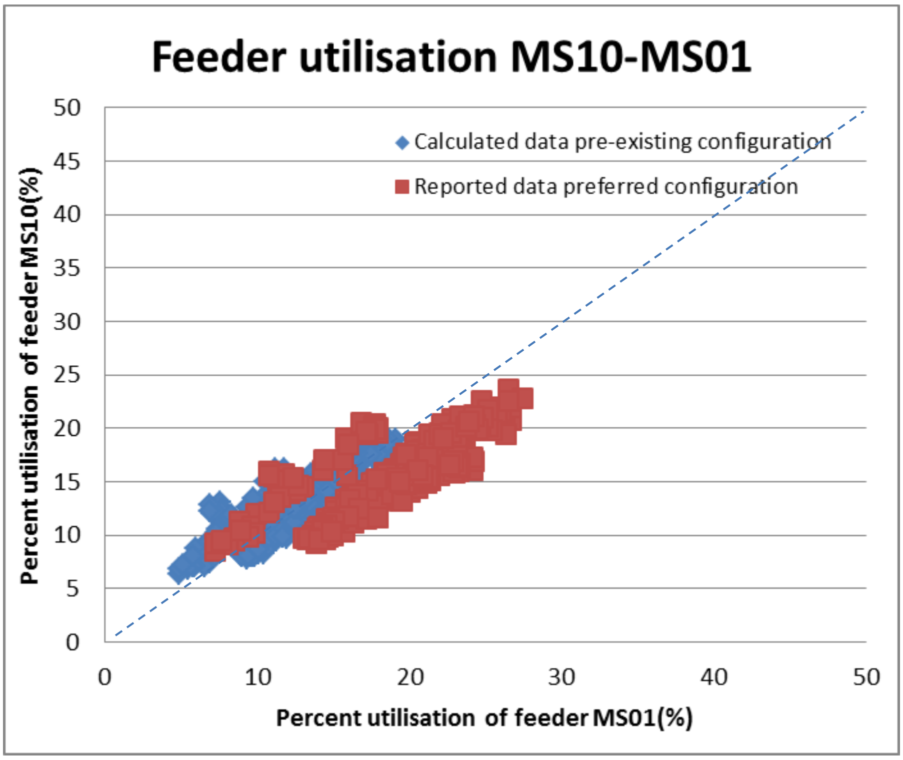


Figure 72 : Measured and estimated feeder utilisation of MS10 and MS01 over week 2

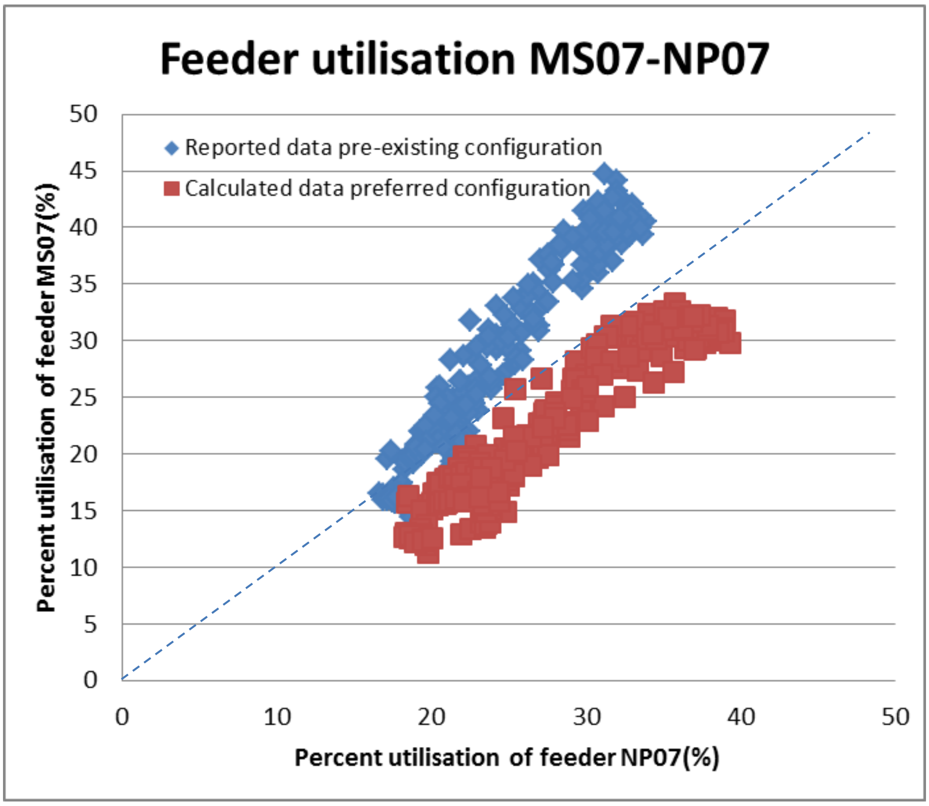


Figure 73 : Measured and estimated feeder utilisation of MS07 and NP07 over week 1

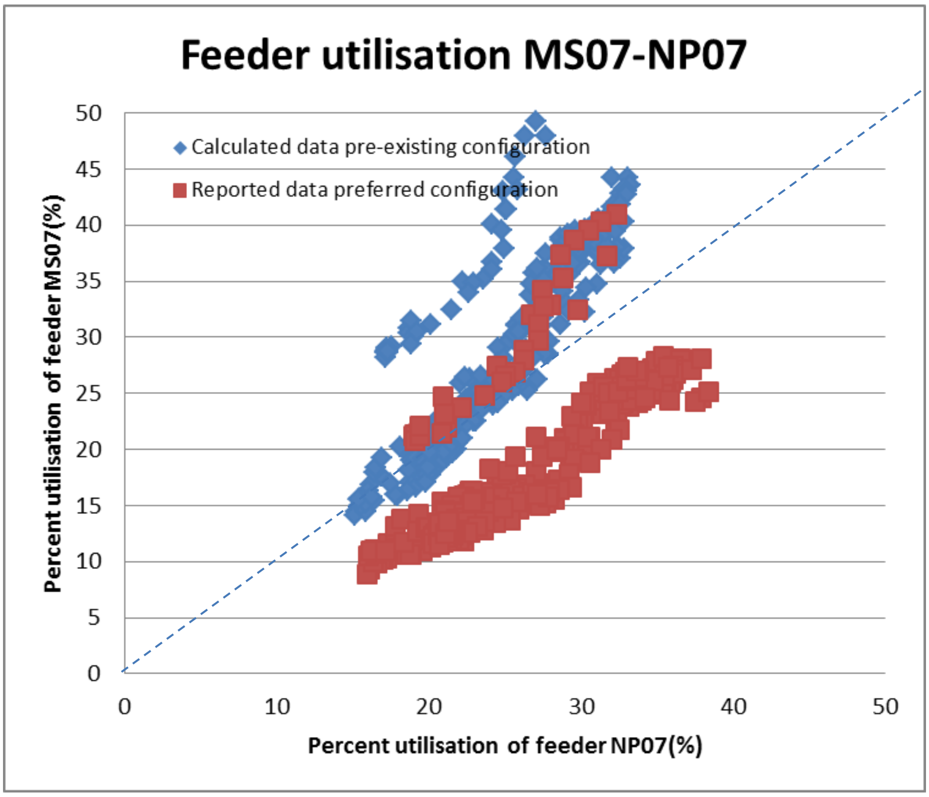


Figure 74 : Measured and estimated feeder utilisation of MS07 and NP07 over week 2

Q Method 2: OHL feeder utilisation results

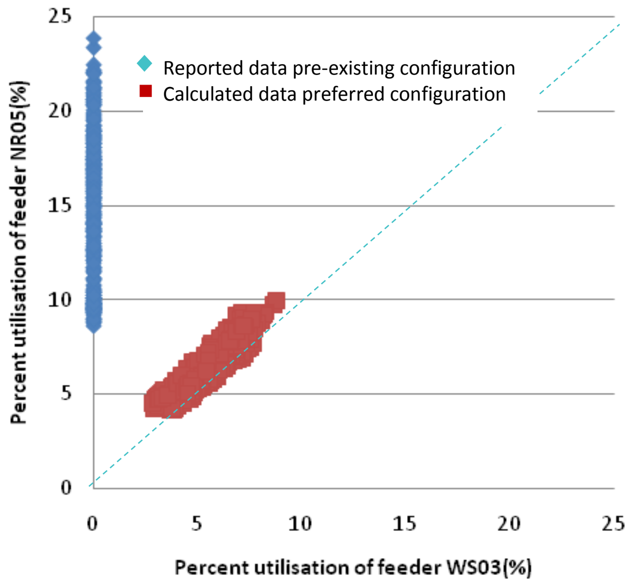


Figure 75: Feeder utilisation for week 1 (WS03/NR05)

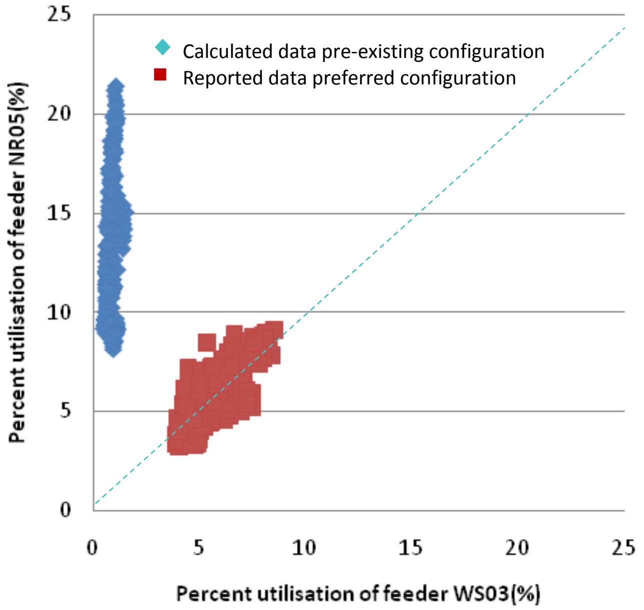


Figure 76: Feeder utilisation for week 2 (WS03/NR05)

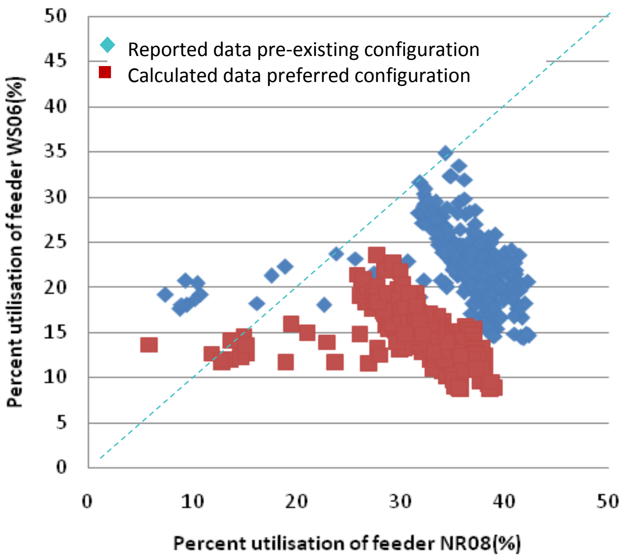


Figure 77: Feeder utilisation for week 1 (NR08/WS06)

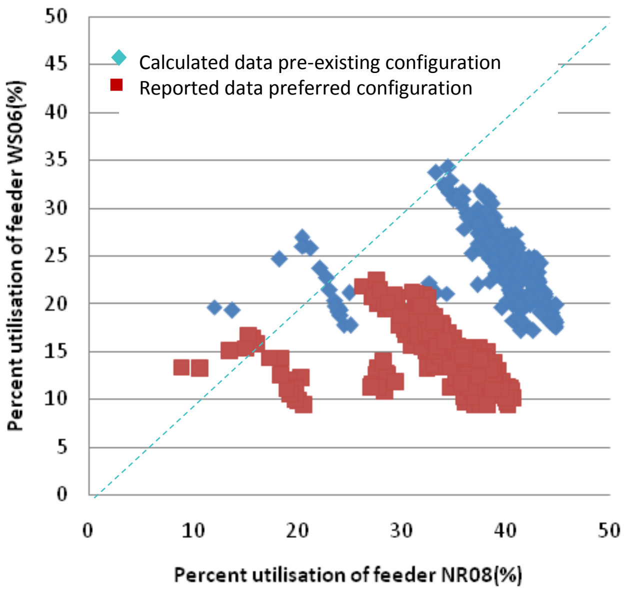


Figure 78: Feeder utilisation for week 2 (NR08/WS06)

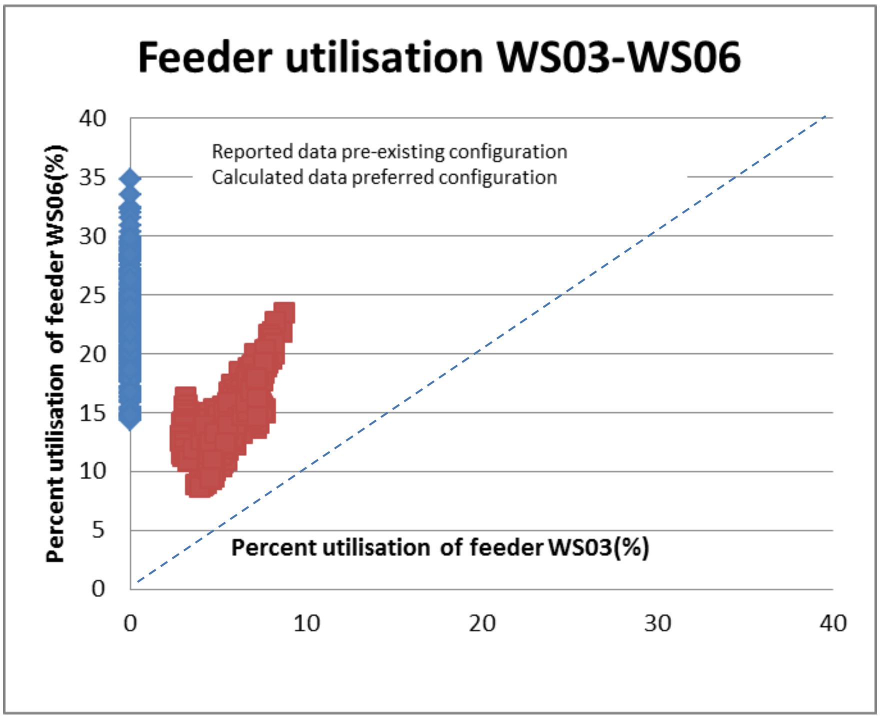


Figure 79 : Measured and estimated feeder utilisation of WS03 and WS06 over week 1

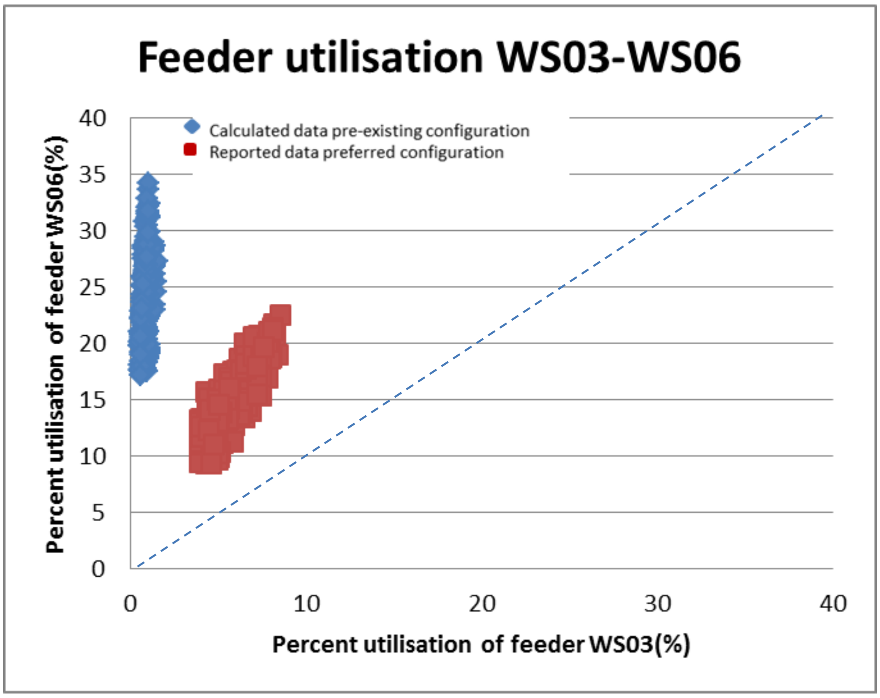


Figure 80 : Measured and estimated feeder utilisation of WS03 and WS06 over week 2

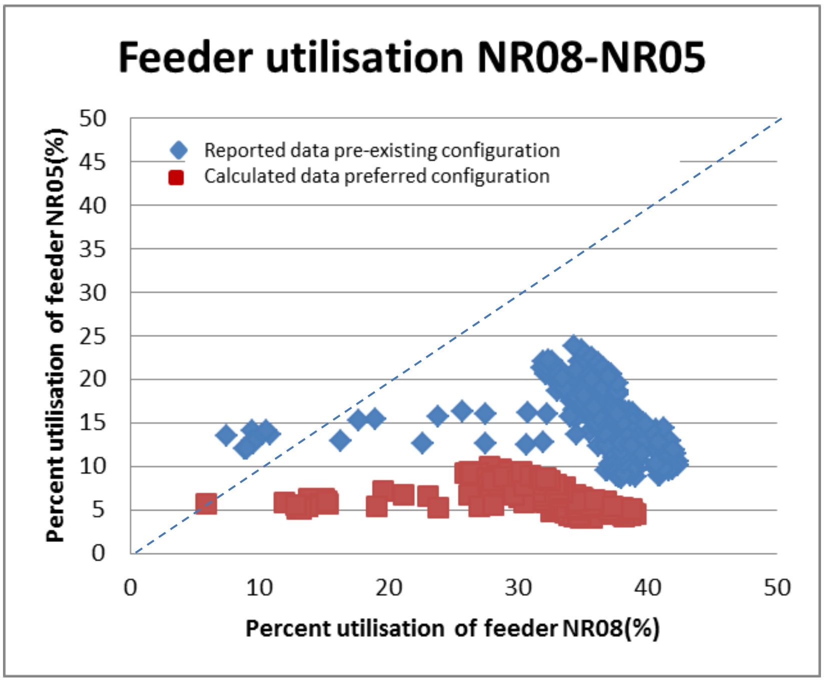


Figure 81 : Measured and estimated feeder utilisation of NR08 and NR05 over week 1

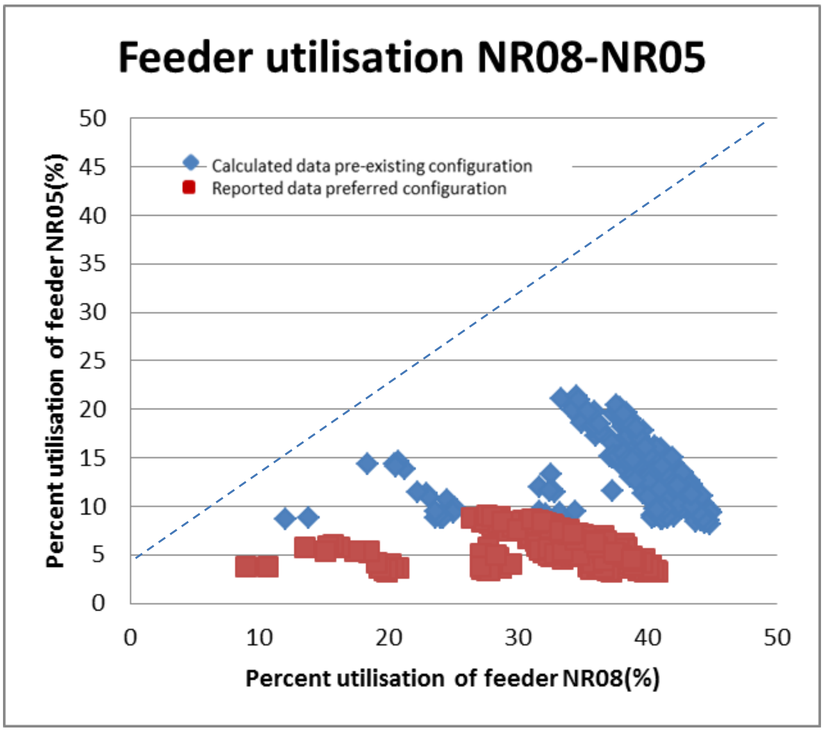


Figure 82 : Measured and estimated feeder utilisation of NR08 and NR05 over week 2

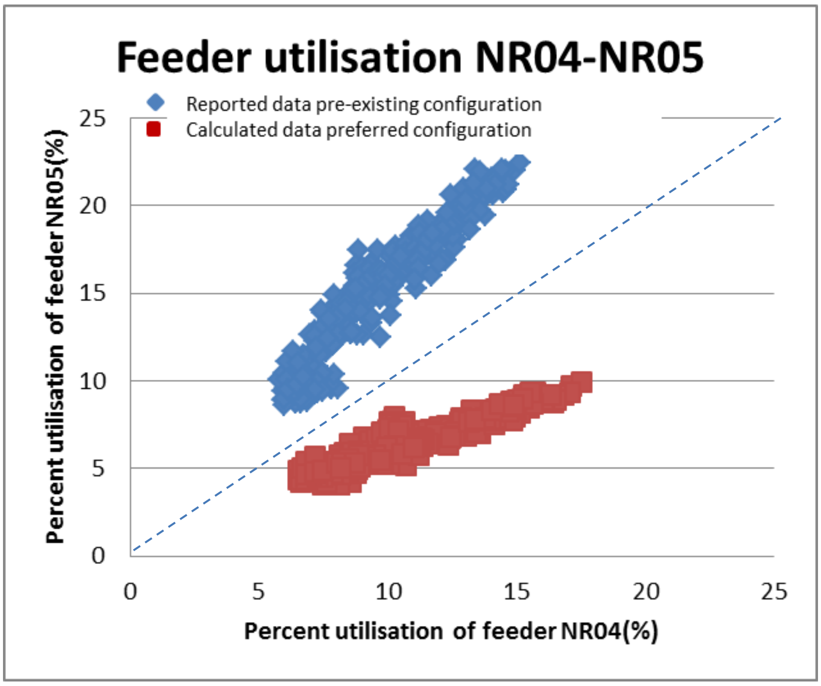


Figure 83 : Measured and estimated feeder utilisation of NR04 and NR05 over week 1

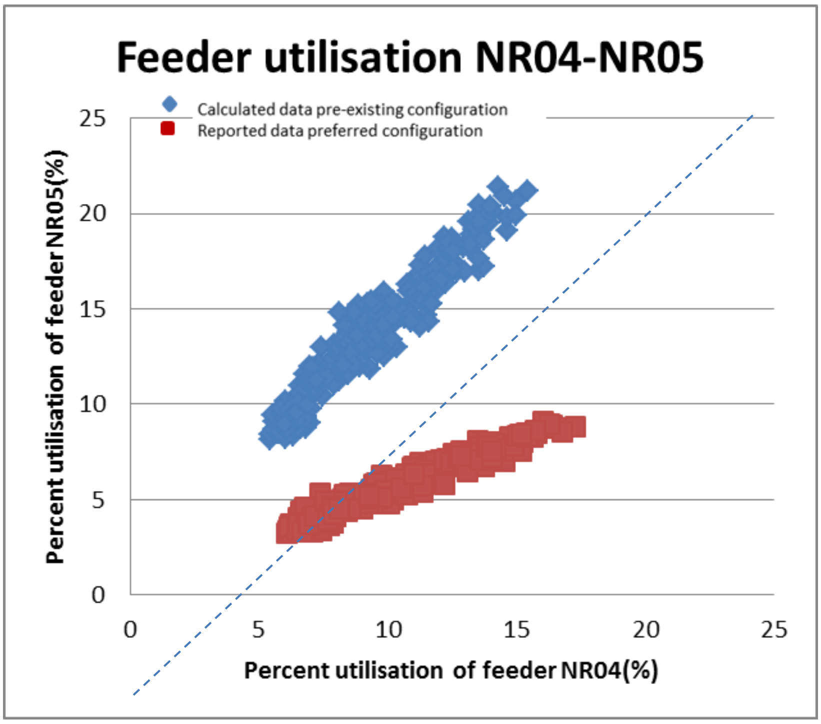


Figure 84 : Measured and estimated feeder utilisation of NR04 and NR05 over week 2

R Method 2: Cable feeder utilisation results

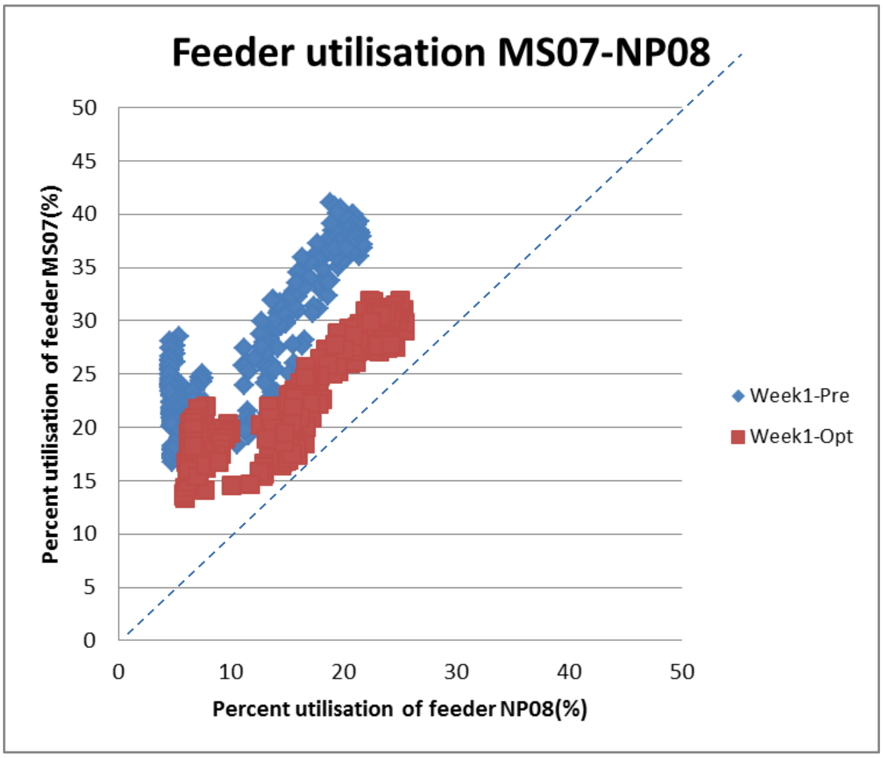


Figure 85 : Feeder utilisation with pre-existing NOP between MS07 and NP08

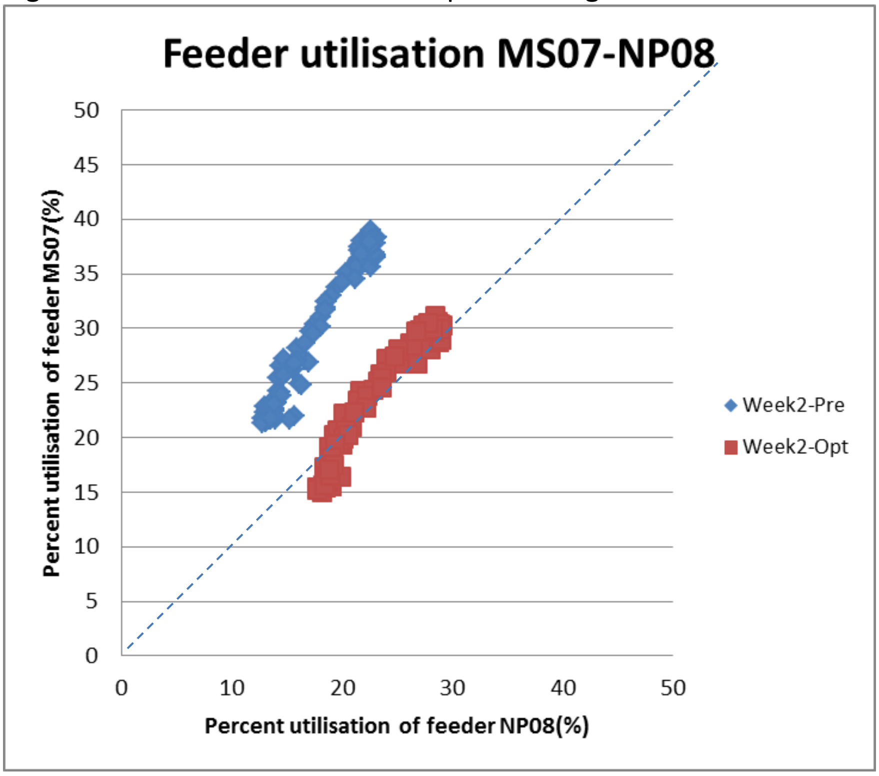


Figure 86 : Feeder utilisation with optimised NOP between MS07 and NP08

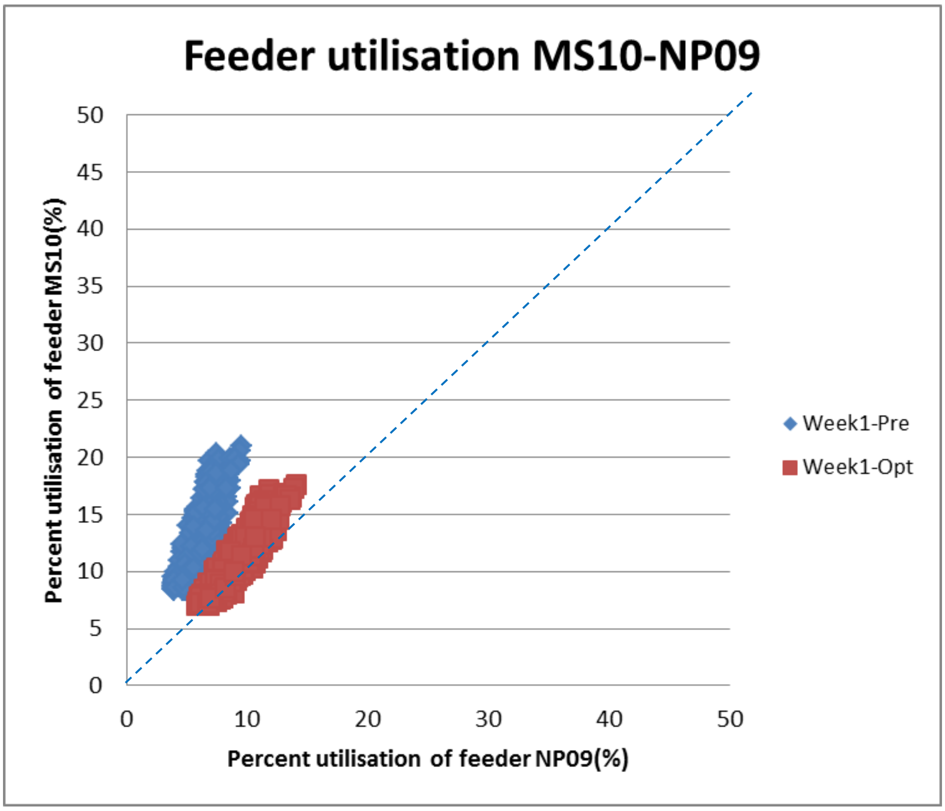


Figure 87 : Feeder utilisation with pre-existing NOP between MS10 and NP09

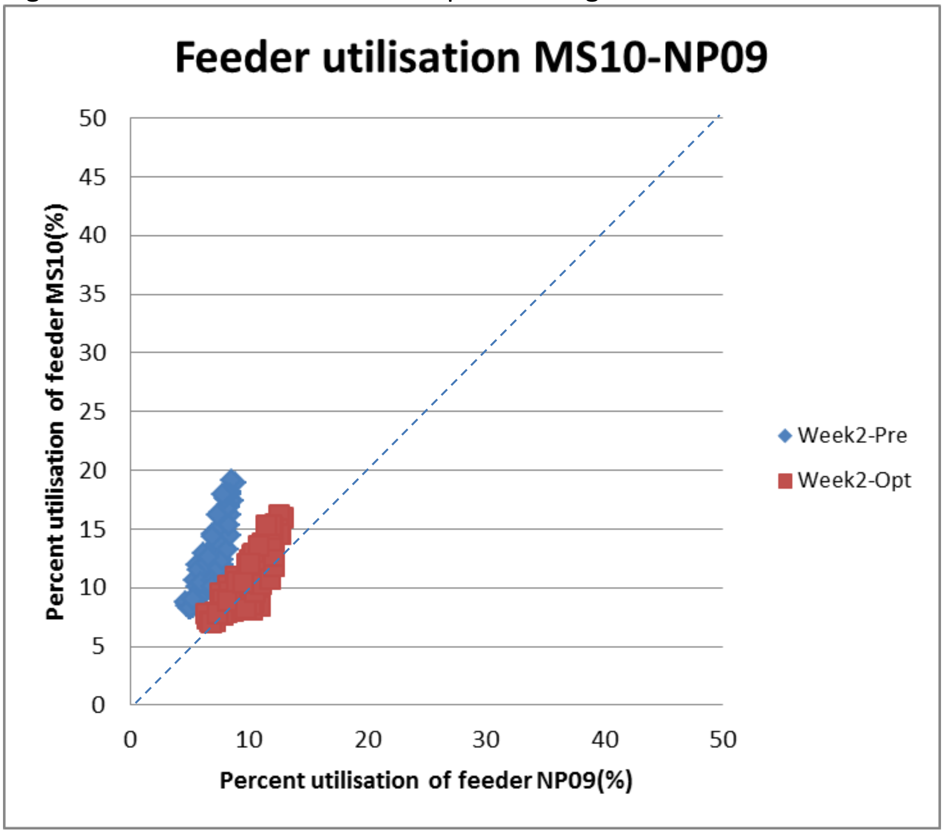


Figure 88 : Feeder utilisation with optimised NOP between MS10 and NP09

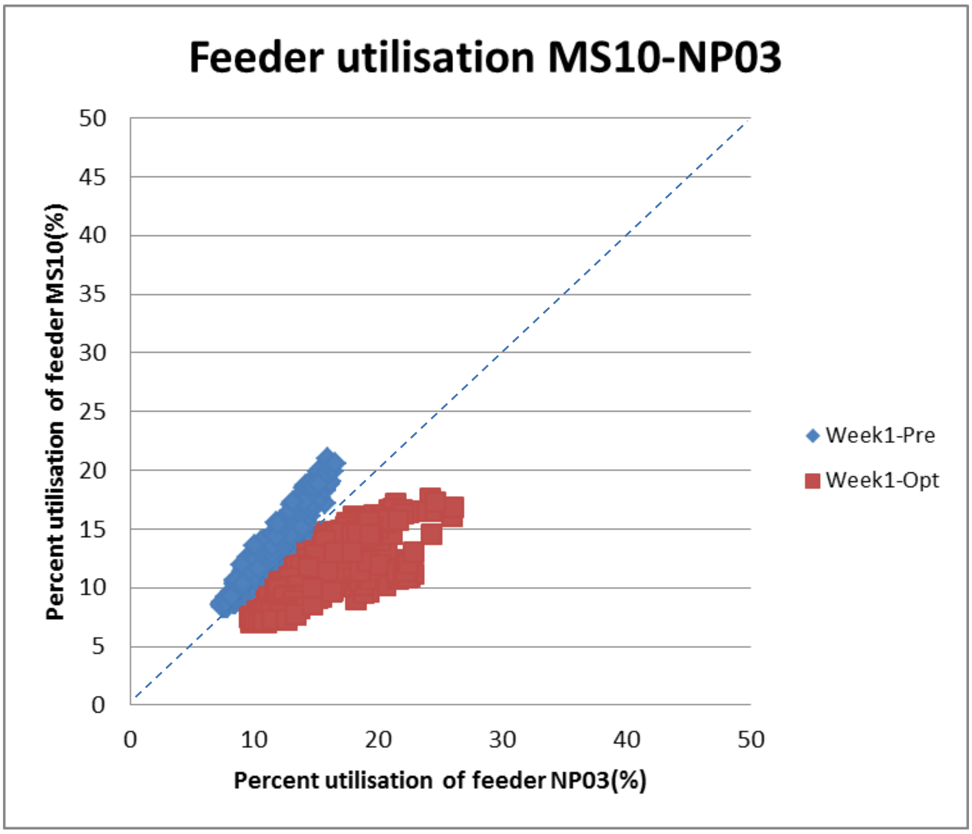


Figure 89 : Feeder utilisation with pre-existing NOP between MS10 and NP03

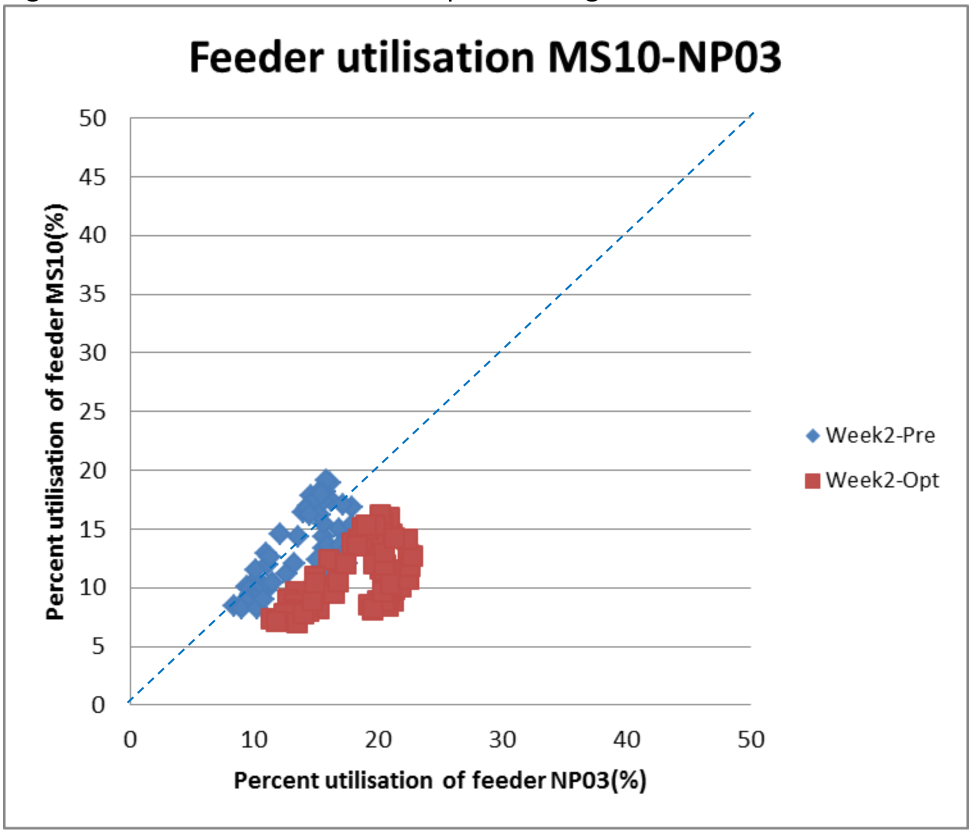


Figure 90 : Feeder customer number with optimised NOP between MS10 and NP03

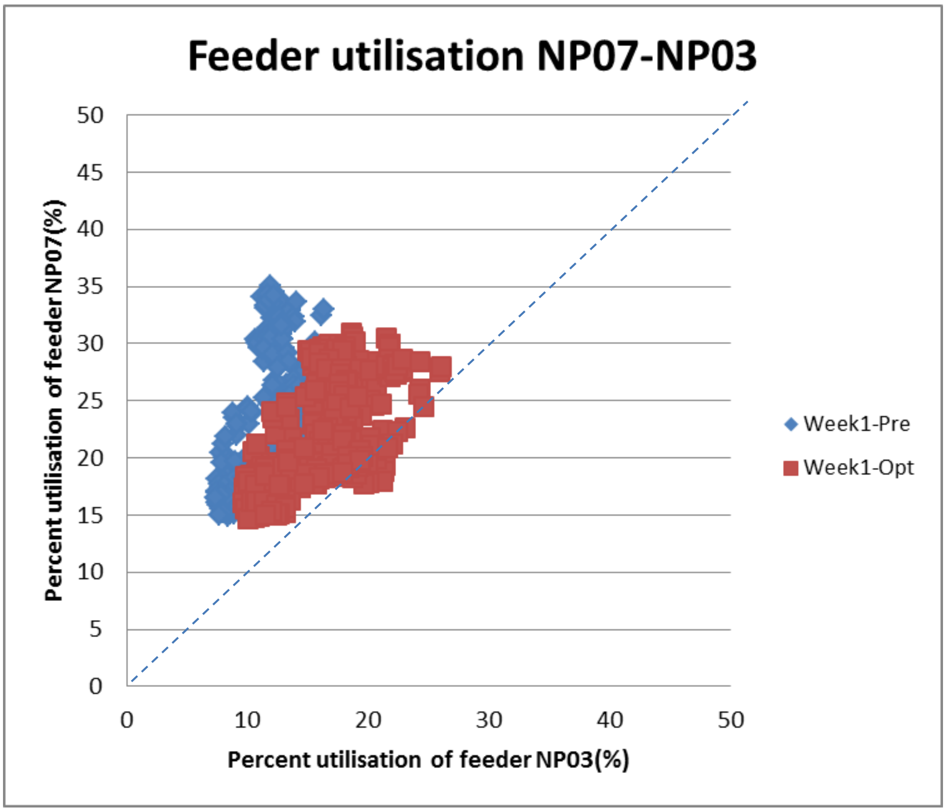


Figure 91 : Feeder utilisation with pre-existing NOP between NP07 and NP03

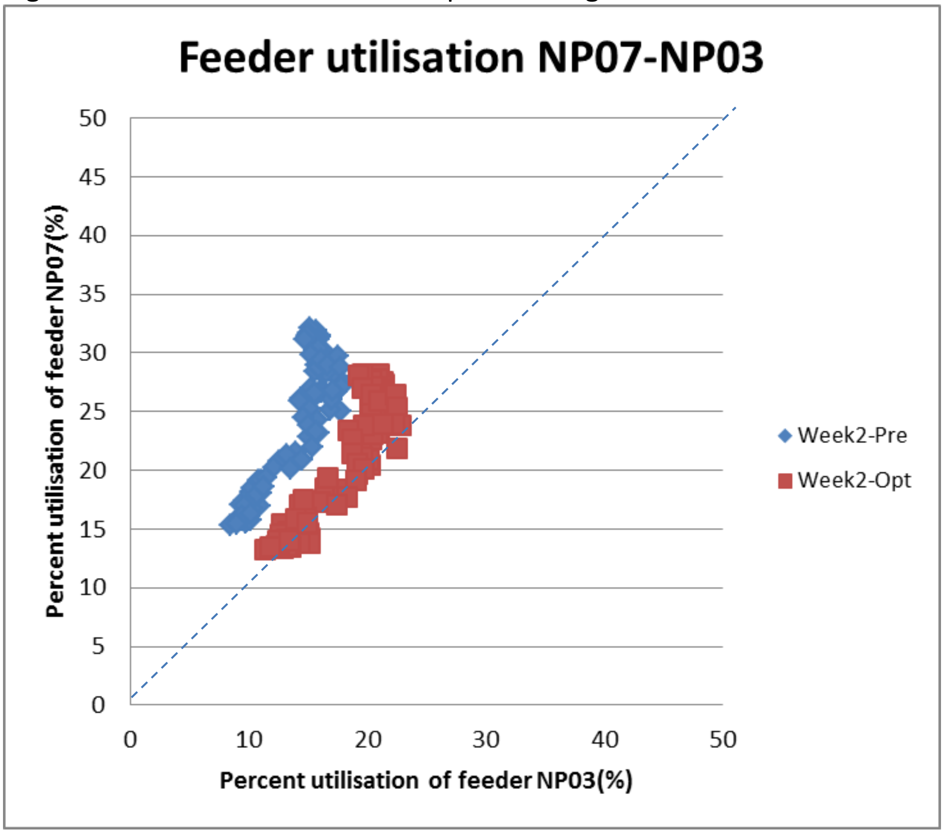


Figure 92 : Feeder customer utilisation with optimised NOP between NP07 and NP03

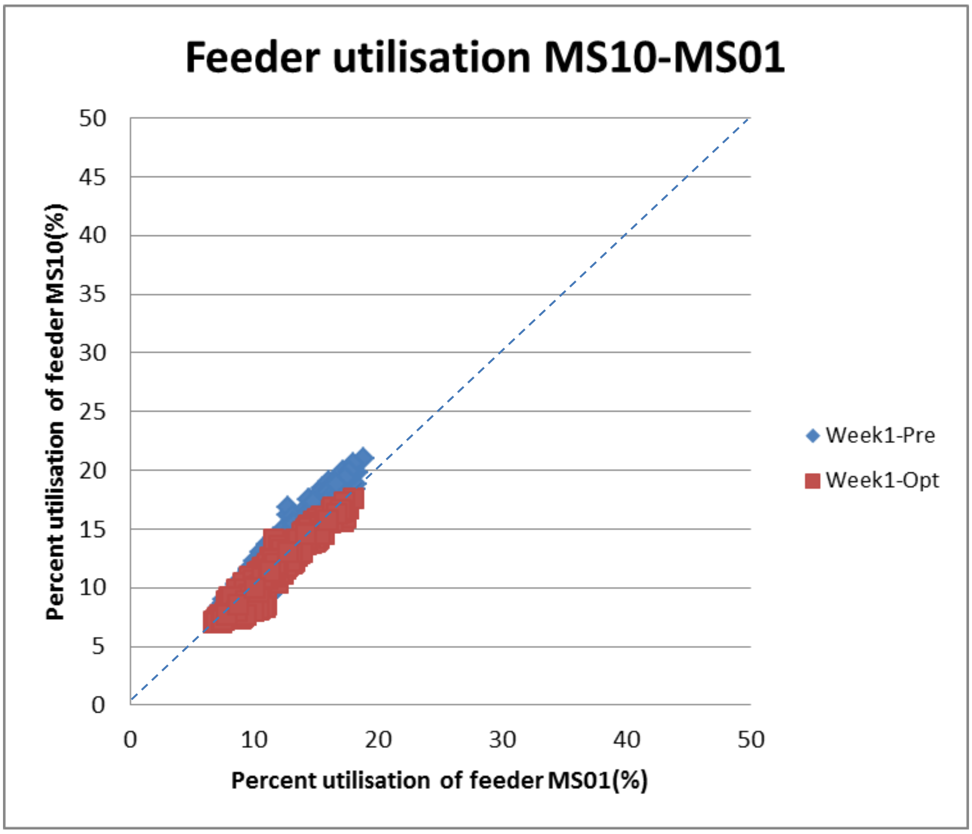


Figure 93 : Feeder utilisation with pre-existing NOP between MS10 and MS01

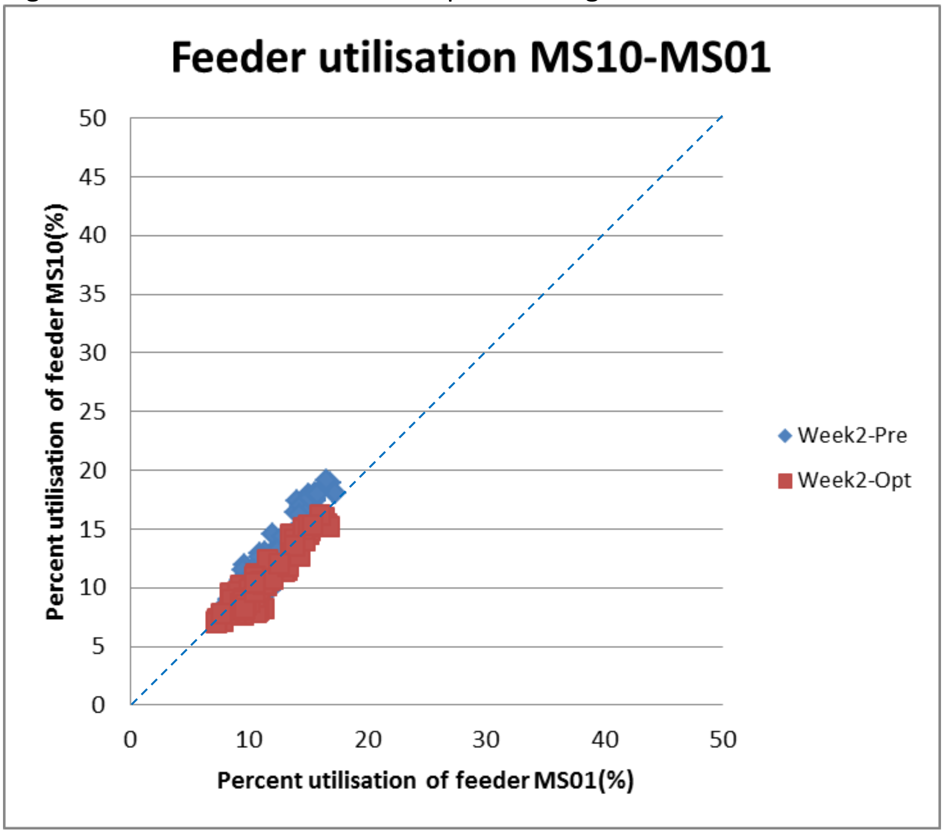


Figure 94 : Feeder customer utilisation with optimised NOP between MS10 and MS01

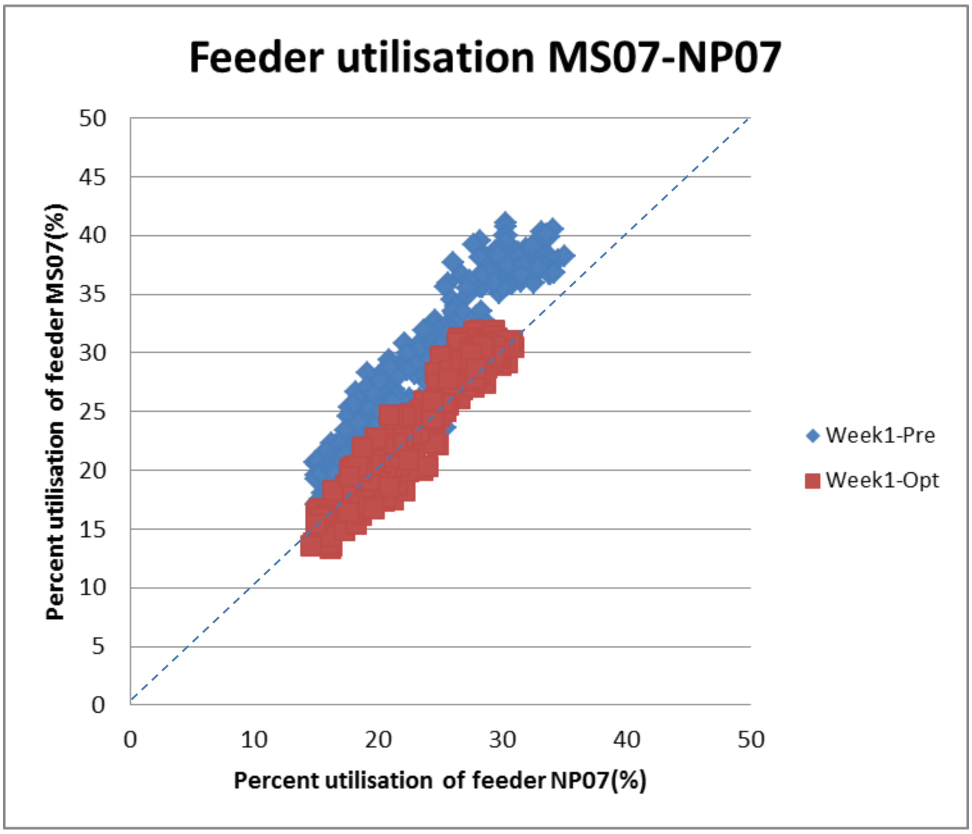


Figure 95 : Feeder utilisation with pre-existing NOP between MS07 and NP07

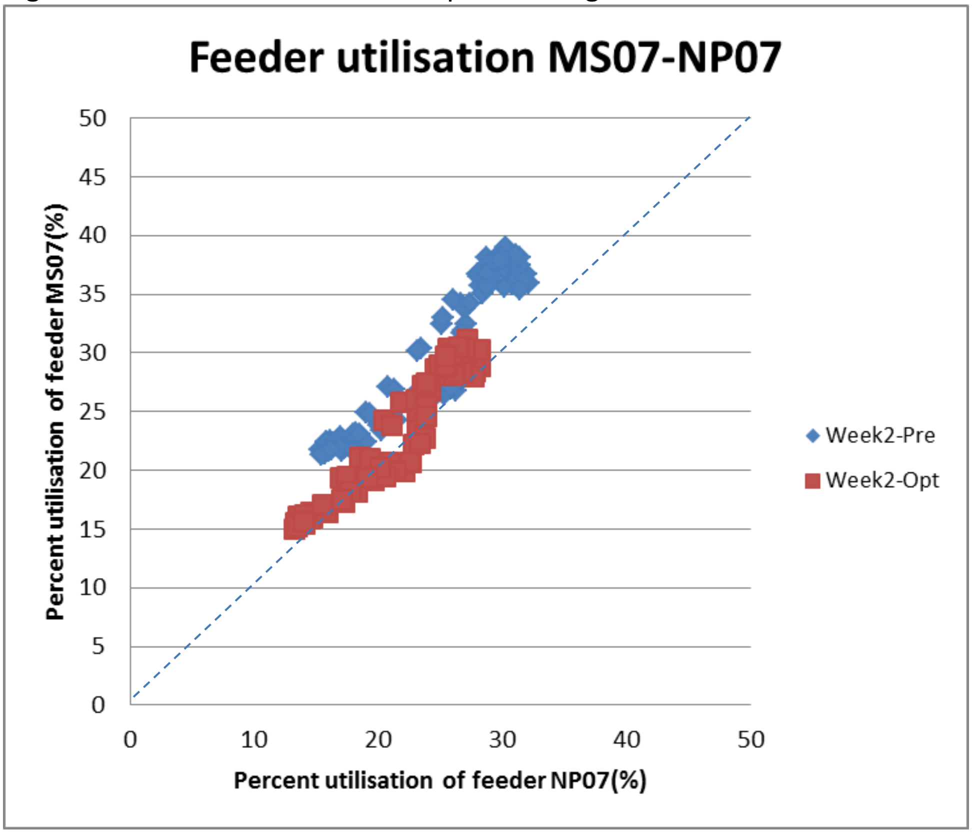


Figure 96 : Feeder customer utilisation with optimised NOP between MS10 and MS01

S Results summary

S.1 Feeder utilisation

The calculated and modelled feeder currents can be analysed in more detail at feeder level. For example, the determined peak measured feeder utilisation is shown in white, while the estimated utilisation based on assumed load distribution is shown in grey for the other configurations. The tables below consider the Utilisation (load on the cable or line as a percentage of its rating) as the measure of capacity headroom that is gained or lost as a result of the open point movement.

The results for the Method 1 determined Overhead line Network are shown Table 37 and Table 38 for trial weeks 1 and 2 respectively.

NOP configuration	Maximum feeder utilisation (%) across all periods				
	WS03	WS06	NR04	NR05	NR08
Pre-existing configuration 0	0	**36**	17	25	23
Configuration 1	4	**39**	19	19	24
Configuration 2	4	**39**	19	16	24

Table 37: Method 1 - Calculated highest feeder utilisations for trial period week 1 for overhead line network

NOP configuration	Maximum feeder utilisation (%) across all periods				
	WS03	WS06	NR04	NR05	NR08
Pre-existing configuration 0	2	**39**	18	24	23
Configuration 1	5	**42**	20	19	23
Configuration 2	5	**42**	20	15	23

Table 38: Method 1 - Calculated highest feeder utilisations for trial period week 2 for overhead line network

Table 39 and Table 40 show the change in feeder utilisation on the cable Network under week 1 and week2 of the trial. Initial inspection shows that there is significant variation in branch utilisation between feeders within the trial network (e.g. MS07 compared to NP09).

NOP configuration	Maximum feeder utilisation (%)						
	NP03	NP07	NP08	NP09	MS01	MS07	MS10
Pre-existing configuration 0	23	34	22	8	18	**45**	20
Configuration 1	21	**39**	23	6	24	33	23

NOP configuration	Maximum feeder utilisation (%)						
Configuration 2	21	**37**	20	12	24	36	21

Table 39: Method 1 - Calculated highest feeder utilisations for trial periods 15-20 May 2014 for Cable network

NOP configuration	Maximum feeder utilisation (%)						
	NP03	NP07	NP08	NP09	MS01	MS07	MS10
Pre-existing configuration	18	33	25	11	19	**51**	20
Configuration 1	16	39	30	7	28	**41**	24
Configuration 2	16	36	28	15	28	**43**	22

Table 40: Method 1 - Calculated highest feeder utilisations for trial periods 17-24 Jun 2014 for Cable Network

Method 2 is designed to increase the headroom on pre-determined feeders within the Network. The corresponding tables for these trial periods are shown below. The loading on NR08 has increased with the addition of an additional 2MW generation at Shank's and consequently the export power through the feeder is increased. Re-adjusting the NOP towards WS06 to allow the generator to supply more local load can only partially reduce this loading as most of this extra load is small rural farms.

NOP configuration	Maximum feeder utilisation (%) across all periods				
	WS03	WS06	NR04	NR05	NR08
Pre-existing configuration 0	0	35	15	24	**42**
Configuration 1	9	24	18	10	**39**

Table 41: Method 2 - Calculated highest feeder utilisations for trial period week 1 for overhead line network

NOP configuration	Maximum feeder utilisation (%) across all periods				
	WS03	WS06	NR04	NR05	NR08
Pre-existing configuration 0	2	34	15	21	**45**
Configuration 1	9	22	17	9	**41**

Table 42: Method 2 - Calculated highest feeder utilisations for trial period week 2 for overhead line network

NOP configuration	Maximum feeder utilisation (%)						
	NP03	NP07	NP08	NP09	MS01	MS07	MS10
Pre-existing configuration 0	17	35	22	10	19	**41**	21
Configuration 1	26	31	25	14	18	**32**	18

Table 43: Method 2 - Calculated highest feeder utilisations for trial periods for Cable network

NOP configuration	Maximum feeder utilisation (%)						
	NP03	NP07	NP08	NP09	MS01	MS07	MS10
Pre-existing configuration 0	18	32	23	9	17	**39**	19
Configuration 1	23	28	29	13	17	**31**	16

Table 44: Method 2 - Calculated highest feeder utilisations for trial periods for Cable Network

S.2 Losses

The tables below show the calculated losses for the pre-existing configuration, for configuration 1 and configuration 2 for methods 1 and method 2 of the overhead line and the cable networks.

Week	Pre-existing NOP configuration (config 0)	Practical preferred Configuration (config 1)	Ideal configuration (config 2)
1	4.7	4.1	4.1
2	5.2	4.6	4.6

Table 45: Method 1 comparison of calculated total losses of OHL Network with configurations in trial period (MWh)

Week	Pre-existing NOP configuration (config 0)	Practical preferred Configuration (config 1)	Ideal configuration (config 2)
1	3.7	3.4	3.4
2	5.1	4.7	4.5

Table 46: Method 1 comparison of calculated total losses of Cable Network with configurations in trial period (MWh)

	Pre-existing configuration	Preferred configuration
Week 1	8.8	10.4
Week 2	7.4	9.0

Table 47 : Method 2 comparison of calculated total losses of OHL Network with configurations in trial period (MWh)

	Pre-existing configuration	Preferred configuration
Week 1	5.04	5.08
Week 2	1.47	1.49

Table 48 : Method 2 comparison of calculated total losses of Cable Network with configurations in trial period (MWh)

It should be noted that the calculated losses are based on the actual measured total feeder loads in that period, and the assumed distribution of load along the feeders. It is important to recognise that the calculated losses would be different if the actual distribution of loads along the feeders were not as assumed.

Although the losses are all calculated through modelling, the magnitude of losses for the greyed out cells use further modelling assumptions:

- Losses for configuration 1 and 2 (if it were implemented) during week 1 can be calculated, using the measured total feeder loads and the assumed distribution of loads along the feeder to calculate magnitudes of individual loads, and then to model the revised circuit configuration using these individual loads.
- Similarly losses for configuration 0 (during week 2) and configuration 2 can be modelled.

Table 45 shows the calculated losses of the OHL network with the pre-existing NOP and preferred NOP over trial weeks using the method 2 configuration. It can be seen that the losses increased by almost 20% compared to the preferred NOP configuration. With the preferred NOP configuration, more loads are transferred to be supplied by the onsite generation, which can decrease the feeder utilisation. However, the loads are supplied via a longer feeder which leads to increased losses. These losses are higher than those listed in Table 47 for two reasons. The trial under method 2 lasted for an extra day and therefore the time scale has increased. In addition the addition of the extra 2MW generation causes extra losses as there is extra current exported.

Table 46 shows the calculated losses of the cable Network with pre-existing NOP and preferred NOP over trial weeks using the method 2 configuration. It can be seen that the losses increased a little with the preferred NOP configuration, whose objective is to balance the feeder utilisation. The time span over which losses were calculated in week 2 is reduced due there being less days data in this configuration as there was a fault occurrence within the trials which meant a more uncertain configuration was implemented during the week trial post fault. However the ratio of losses between the two configurations is in keeping with week 1.

Pulling the losses analysis together, data from this trial suggests:

- A revised configuration of NOPs compared to the pre-existing configuration should lead to modest improvements in network losses

- Improvements are found to be up to 12% using method 1 (loss minimisation) configurations.
- Increases in losses are found using method 2 (capacity headroom maximisation).

A summary of these results is shown below

Method	Network	Change in losses
1	OHL	-12%
1	Cable	-8%
2	OHL	+30%
2	Cable	+0.8%

Table 49 : Comparison of losses variation

S.3 Minimal node voltage

Table 50 to Table 53 show the calculated minimal node voltage for the pre-existing configuration and practical trial for the method 1 configurations of the OHL and cable networks and method 2 configurations respectively. It should be noted that the calculated voltages are based on the actual measured total feeder loads in that period, and the assumed distribution of load along the feeders. It is important to recognise that the voltages would be different if the actual distribution of loads along the feeders were not as assumed. The voltage at the primary substations is set to 11.3kV.

Magnitude of minimal voltages for the grey shaded cells can be calculated, but use further modelling assumptions.

- Voltages for configuration 1 (if it were implemented) during week 1 can be calculated, using the measured total feeder loads and the assumed distribution of loads along the feeder to calculate magnitudes of individual loads, and then to model the revised circuit configuration using these individual loads.
- Similarly voltages for configuration 2 (not actually implemented) can be modelled.

There is no significant change in voltage on the cable network. However, there are slight improvements on the OHL network as shown below.

Week	Pre-existing NOP configuration (config 0)	Practical preferred Configuration (config 1)	Ideal configuration (config 2)
1	10.89	10.93	10.95
2	10.83	10.86	10.85

Table 50 : Method 1- Summary of calculated minimum voltages (kV) on overhead line network

Week	Pre-existing NOP configuration (config 0)	Practical preferred Configuration (config 1)	Ideal configuration (config 2)
1	11.17	11.17	11.18
2	11.19	11.19	11.20

Table 51 : Method 1 -Summary of calculated minimum voltages (kV) on cable line network

Week	Pre-existing configuration	Preferred configuration
1	10.97	10.62
2	11.00	10.64

Table 52 : Method 2- Summary of calculated minimum voltages (kV) on overhead line network

Week	Pre-existing configuration	Preferred configuration
1	11.19	11.14
2	11.19	11.17

Table 53: Method 2 -Summary of calculated minimum voltages (kV) on cable line network

S.4 Customer Numbers

Table 54 to Table 57 show the change in customer numbers of the OH network and cable network and under different configurations for method 1 and method 2 respectively.

NOP configuration	Customer Number				
	WS03	WS06	NR04	NR05	NR08
Pre-existing configuration 0	101	1276	2059	1585	1566
Configuration 1	381	1403	2326	1038	1439
Configuration 2	386	1398	2326	746	1731

Table 54: Method 1- customer numbers of OH network with different configurations

NOP configuration	Customer Number						
	NP03	NP07	NP08	NP09	MS01	MS07	MS10
Pre-existing configuration	1480	793	36	876	1332	1014	2042
Configuration 1	1380	1062	57	150	1460	717	2747
Configuration 2	1380	1057	57	512	1460	722	2385

Table 55: Method 1- Customer numbers of cable network with different configurations

NOP configuration	Customer Number				
	WS03	WS06	NR04	NR05	NR08
Pre-existing configuration	101	1276	2059	1585	1566
Preferred configuration	549	1063	2326	578	2071

Table 56:Method 2- customer numbers of OH network with different configurations

NOP configuration	Customer Number						
	NP03	NP07	NP08	NP09	MS01	MS07	MS10
Pre-existing configuration	1480	793	36	876	1332	1014	2042
Preferred configuration	1463	1051	57	1276	1320	728	1678

Table 57: Method 2- Customer numbers of cable network with different configurations

Under method 1, a change of cable network happens on feeder pair NP09 and MS10 with the loads transferred at three distribution substations (Sandywell Drive, Willen Park Avenue and Landsborough Gate), where the numbers are 363, 276 and 86 respectively. Similarly, the substation St George Road with 267 customers on OH network has an impact on the customer number variation between feeder NR04 and NR05.

Under the method 2 to balance the feeder utilisation on the overhead Network loads are transferred from NR05 to WS03, NR04 and NR08, which contributes to the decrease on NR05. Meanwhile, loads are transferred from WS06 to NR08 to make use of the onsite generation, which leads to the increase of customer number on NR08.

Using the method 2 configuration to look at changes to the customer numbers indicates that the transfer of distribution substation Sovereign Drive and Hainault Avenue with customer numbers 400 and 265 respectively, which lead to the increase of NP07 and NP09, and decrease of MS07 and MS10.

A summary of these results is shown below

Method	Network	Decrease in no of customers at risk due to a feeder event
1	OHL	+13%
1	Cable	+34%
2	OHL	+13%
2	Cable	-18%

Table 58 : Comparison of customer number variation

S.5 Time varying switching benefits

The following tables show the calculated benefits that can be gained by switching the circuits in a time varying manner under Method 1 and Method 2 re-configurations on the Networks over the 10 sample days compared to the nominal configuration.

		Min Voltage (kV)		Max Branch loading (%)		Max Feeder utilisation (%)		Losses (MWh)	
Season		Nominal	Method 1	Nominal	Method 1	Nominal	Method 1	Nominal	Method 1
Winter	Weekday	10.7	10.9	45.8	44.1	40.4	44.1	1.8	1.45
	Weekend	10.7	10.8	45	43.1	40.4	43.1	1.89	1.52
Spring	Weekday	11	11.1	33.6	33.1	29.1	31.5	0.63	0.53
	Weekend	11	11	32.9	31.7	28.8	31.3	0.71	0.59
Summer	Weekday	10.8	10.8	38.3	37.1	24.1	25.7	0.61	0.51
	Weekend	11.1	11.2	37	36.7	23.7	23.8	0.53	0.44
High Summer	Weekday	11	11.1	33.17	33.21	24.6	26.7	0.57	0.49
	Weekend	11.1	11.1	33.6	33.4	23.2	25.3	0.57	0.48
Autumn	Weekday	11	11	39	38.1	35.4	38.1	0.78	0.65
	Weekend	10.8	10.9	39.7	37.3	33.1	37.3	1.02	0.85

Table 59: Method 1 –Calculated OHL Network switching benefits

		Min Voltage (kV)		Max Branch loading (%)		Max Feeder utilisation (%)		Losses (MWh)	
Season		Nominal	Method 1	Nominal	Method 1	Nominal	Method 1	Nominal	Method 1
Winter	Weekday	11.2	11.2	44.1	42.9	44.1	42.8	1.26	1.13
	Weekend	11.1	11.2	38.8	35.8	36.5	34.9	1.03	0.97
Spring	Weekday	11.2	11.2	45.3	42.3	45.3	40.9	1	0.89
	Weekend	11.2	11.2	32	31.6	32	30.7	0.62	0.58
Summer	Weekday	11.2	11.2	43.7	39.5	43.7	37.2	0.88	0.78
	Weekend	11.2	11.2	29.6	28.9	28.8	28.2	0.53	0.5
High Summer	Weekday	11.2	11.2	45.2	37.3	45.2	35.1	0.89	0.79
	Weekend	11.2	11.2	31.7	25.8	30.7	25.7	0.54	0.52
Autumn	Weekday	11.2	11.2	46.5	42.2	46.5	39.9	1.06	0.94
	Weekend	11.2	11.2	35.6	35.6	34.5	34.5	0.72	0.69

Table 60: Method 1 –Calculated Cable Network switching benefits

		Min Voltage (kV)		Max Branch loading (%)		Max Feeder utilisation (%)		Losses (MWh)	
		Nominal	Method 2	Nominal	Method 2	Nominal	Method 2	Nominal	Method 2
Winter	Weekday	10.7	10.4	45.8	49	40.4	28.1	1.8	2.7
	Weekend	10.7	10.4	45	47.7	40.4	28.4	1.9	2.8
Spring	Weekday	11	10.2	33.6	43.5	29.1	19.7	0.6	1.8
	Weekend	11	10.2	**32.9**	**44.3**	28.8	19.6	0.7	2
Summer	Weekday	10.8	10.3	38.3	45.4	24.1	17.6	0.6	1.7
	Weekend	11.1	10.4	37	34	23.7	18.4	0.5	1.4
High Summer	Weekday	11	10.2	33.2	42.4	24.6	16	0.6	1.8
	Weekend	11.1	10.3	33.6	41.3	23.2	16.1	0.6	1.7
Autumn	Weekday	11	10.2	39	43.3	35.4	24.5	0.8	2.1
	Weekend	10.8	10.2	39.7	52.1	33.1	23	1	1.8

Table 61 :Method 2 –Calculated OHL Network switching benefits

NOP		Min Voltage (kV)		Max Branch loading (%)		Max Feeder utilisation (%)		Losses (MWh)	
		Nominal	Method 2	Nominal	Method 2	Nominal	Method 2	Nominal	Method 2
Winter	Weekday	11.2	11.1	44.1	51	44.1	40.9	1.3	1.4
	Weekend	11.1	11.1	38.8	43.6	36.5	30.3	1	1
Spring	Weekday	11.2	11.1	45.3	52.2	45.3	41.2	1	1.1
	Weekend	11.2	11.2	32	34.4	32	27.6	0.6	0.6
Summer	Weekday	11.2	11.1	43.7	46.4	43.7	33.7	0.9	1
	Weekend	11.2	11.2	29.6	35.4	28.8	26.1	0.5	0.6
High Summer	Weekday	11.2	11.1	45.2	49.3	45.2	39.8	0.9	1
	Weekend	11.2	11.2	31.7	31.9	30.7	27.7	0.5	0.6
Autumn	Weekday	11.2	11.1	46.5	51.7	46.5	40.6	1.1	1.1
	Weekend	11.2	11.2	35.6	40.8	34.5	30.4	0.7	0.7

Table 62 :Method 2 –Calculated Cable Network switching benefits

A summary of these results is shown below

Method	Network	Voltage limits increase (trial value)	Benefit – headroom increase on primary feeder line (trial value)	Change in losses (trial value)
1	OHL	0% to +2% (+0.3%)	-0% to -12% (-10%)	-20 % to -14% (-12%)
1	Cable	0% to +1% (0%)	0% to +22% (+20%)	-11% to -4% (-8%)
2	OHL	0% to -7% (-3%)	20% to 30% (+10%)	47% to +200% (+30%)
2	Cable	0% to -1% (-0.5%)	7% to 22% (+20%)	0% to +20% (+0.8%)

Table 41: Comparison of benefit gains

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