Optimising Asset Management Using Predictive Analytics and Discrete Event Simulation: PAM System

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PAM Analytics

- Founded in April 2016 to develop further and commercialise PAM (its Predictive Asset Management system).
- PAM Analytics is working with water companies and is in discussion with engineering consultancies, framework providers and pump manufacturers.

PAM

- PAM started as a project for a major UK water company.
- At the end of the project PAM Analytics carried out market research and concluded that PAM had great potential as a predictive asset management system for extending asset lifetimes and optimising asset management.
- Awarded the Build 2019 Infrastructure Award for:
  - best in operational level asset management – UK
  - most innovative infrastructure asset management support solution.
- Winner of the ‘Best Innovation – Water’ category in the UK Energy Innovation Awards 2019.
- Successful in the Dragons’ Den Innovation Event organised by Bristol Water, 2019.

- Asset Management Optimisation
  - Business Challenge and Solution
  - Optimal Intervention Frequency
- PAM System
  - Innovative Features
  - Schema
  - Planning Levels Optimisation
  - Input Data and Output Data
- Survival Analysis
  - Kaplan Meier Analysis and Cox Proportional Hazards Model
- PAM Time to Failure Transformations Module (*data preparation module*)
  - Overlapping and Nested Maintenance and Failure Records
- PAM Asset Key Performance Indicators Module *(empirical results output)*
  - Dependence of Failure on Intervention History
- PAM Predicted Maintenance Interventions Module (Operational Asset Management Optimisation)
  - Example Survival Model (Wet Well Submersible Pumps)
  - Assets in Greatest Need of Proactive Maintenance

- PAM Asset Deterioration Curves Module (Tactical Asset Management Optimisation)
  - Deterioration Curves
  - Hazard Rate Curve
- PAM Asset Survival Simulations Module (Strategic Asset Management Optimisation)
  - Simulation Model and Risk Tolerance
  - Example Penalty Risk Simulation
- PAM Proof of Concept and Implementation
- Conclusion

Business Challenge

- Asset-rich industries face a range of increasing financial, environmental and regulatory costs and demands. This requires assets to work harder and to higher standards.
- The risk of asset failure is increased by these demands and asset management policies that are exclusively or almost exclusively reactive.
- More frequent and more severe asset failure has adverse effects on the environment, the organisation's operational and financial performance.

Solution

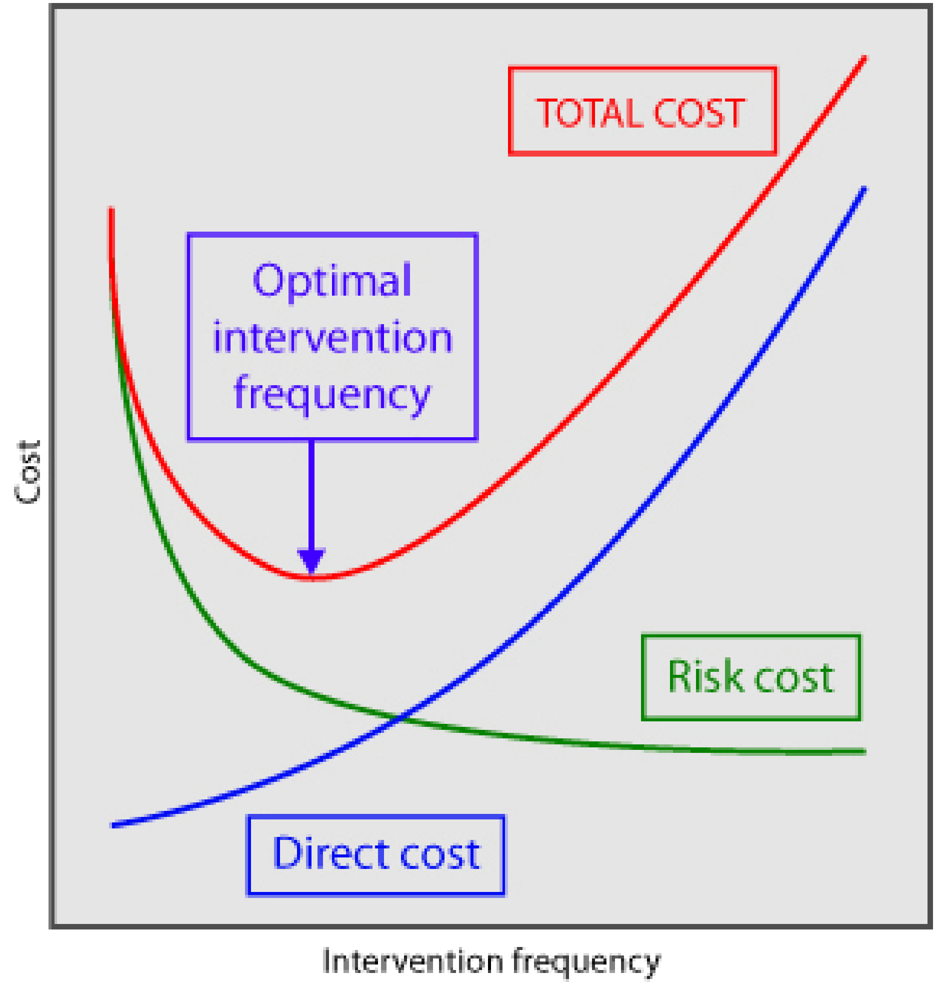
PAM (PAM Analytics' Predictive Asset Management system).

PAM:

- is an innovative infrastructure asset management decision support system that uses predictive analytics and simulation to model, simulate and optimise asset performance at individual asset level and at the operational, tactical and strategic levels
- allows users to gain insight and understanding into asset performance and failure
- changes the asset management policy from reactive fail-and-fix to proactive predict-and-prevent
- reduces the risk of asset failure, extends asset lifetimes and reduces asset management costs.

The objective is to find the asset management policy that optimises the trade-off between the risk cost of asset failure and replacement, and the direct cost of asset maintenance. The risk cost includes the consequence cost of asset failure, for example fines from regulators.

PAM finds the optimal intervention frequency, i.e. the frequency that minimises the total asset management cost.



- The innovative and unique features of PAM derive from the fact that it uses predictive analytics rather than business intelligence.
  - Business intelligence looks backwards to report what *has* happened.
  - Predictive analytics uses historical data to develop models for predicting what *is likely to* happen under a range of different scenarios.

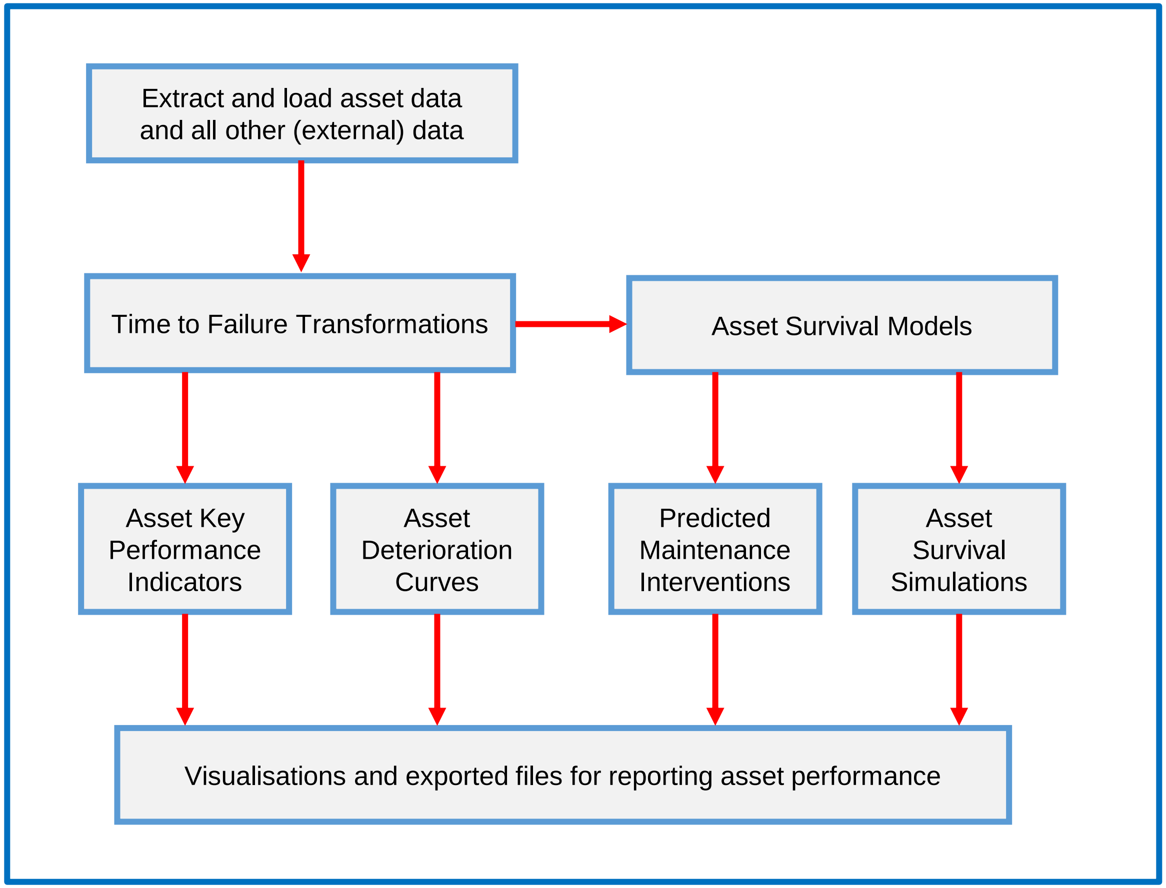
- Complete predictive asset management decision support tool. Loads, prepares and models the data, and outputs the results for viewing and downloading using visualisation software.

- Asset management optimisation. Optimises asset management at individual asset level and at the operational, tactical and strategic levels.

- Factors that contribute to asset failure. Identifies the factors that contribute to asset failure.

- Models each asset as a unique entity with its own *dynamic* risk of failure profile. Current asset management systems model the risk of failure of *groups of assets as a static* phenomenon where each member of the group has the same risk of failure profile.

PAM System Schema



Module Functions

Data Preparation
- Data extraction and load
- Time to failure transformations

Key Performance Indicators (*output module)*
- Empirical analysis of failures
- Failure rate curve

Modelling (‘*engine’ at centre of PAM)*
- Asset survival models

Operational (*output module)*
- Predicted Maintenance Interventions

Tactical (*output module*)
- Asset deterioration curves

Strategic (*output module*)
- Asset survival simulations

Operational Level (Predicted Maintenance Interventions Module)

- Identify the assets at greatest risk of imminent failure so that they can be scheduled for proactive maintenance to reduce their risks of failure rather than repaired or replaced after they fail. The cost of operational asset management is minimised.
- The asset survival models show that this leads to a virtuous proactive maintenance feedback policy.

Tactical Level (Asset Deterioration Curves Module)

- Deterioration curves and tables that show how different values of a factor, for example the amount of proactive maintenance and the demand placed on each asset, affect the risk of asset failure.
- Determine the values of factors that optimise asset performance.

Strategic Level (Asset Survival Simulations Module)

- Simulate the financial implications of a range of asset maintenance and replacement policies to determine the optimal, i.e. most cost-effective, policy subject to a range of operational constraints, for example the organisation’s maintenance capacity and attitude to the risk of asset failure.

PAM Analytics Predictive Asset Management

PAM System
Input Data and Output Data

Input Data Source/Type	Examples
Asset register	Type, power, manufacturer, installation date, design specification
Work orders	Asset maintenance and failure history
Asset usage	Hours run
Asset status	Asset criticalities
Asset costs	Asset maintenance and replacement costs
Other costs	Consequence costs resulting from asset failure
Demand on each asset	Population in catchment area of each asset
Site location	Postcode district
Land use	Proportions of developed land and green belt land
Seasonal factors	Holiday location
Weather	Rainfall, temperature
Extreme events	Flooding, extreme temperatures

Output data: A file at asset-intervention level for the analysis and modelling modules.

- Survival analysis is the branch of statistics that deals with the analysis of times until the event of interest, asset failure in this case, occurs.
- It consists of two components, Kaplan Meier analysis and hazard models.

Kaplan Meier Analysis

- Developed in 1958 and still regarded as a major advance in statistical science. Also known as the product limit estimator because it is based on the product of a set of conditional probabilities.
- PAM uses Kaplan Meier analysis to generate asset deterioration (risk) curves in the Asset Deterioration Curves module for tactical asset management.
- Deterioration curves show how different values of a factor, for example the number of proactive interventions, affect the risk of failure as assets are used.
- Kaplan Meier analysis uses the concepts of risk sets and censored assets.

Cox Proportional Hazards Model

- Proposed by Sir David Cox in 1972 in a seminal paper in the *Journal of the Royal Statistical Society.* The paper is ranked in the top three most cited papers in statistics.
- PAM uses the Cox proportional hazards model to model asset failure.
- The output is the cumulative hazard of each asset at ‘each time’. Cumulative hazard is the accumulated risk of failure (it is sometimes described as the potential for failure).

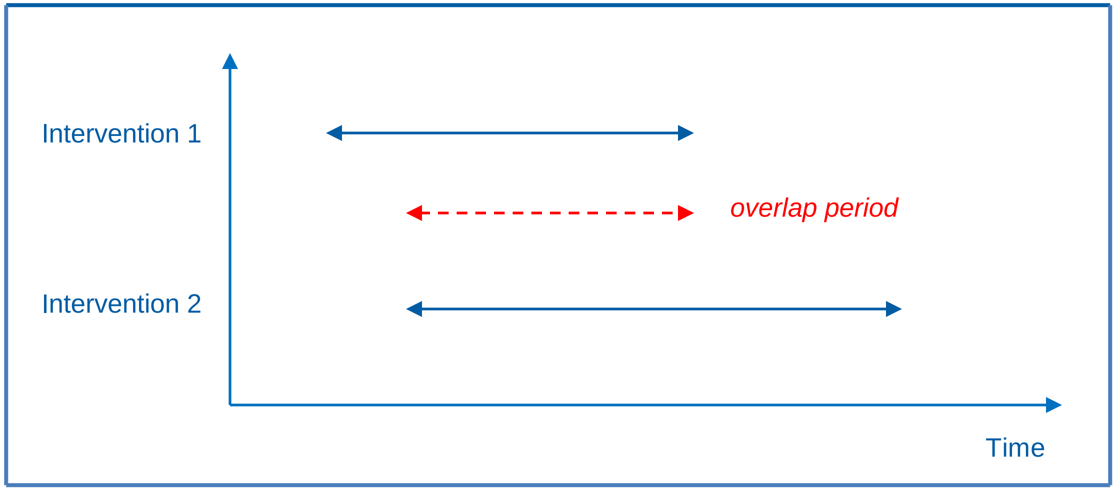
PAM Time to Failure Transformations Module

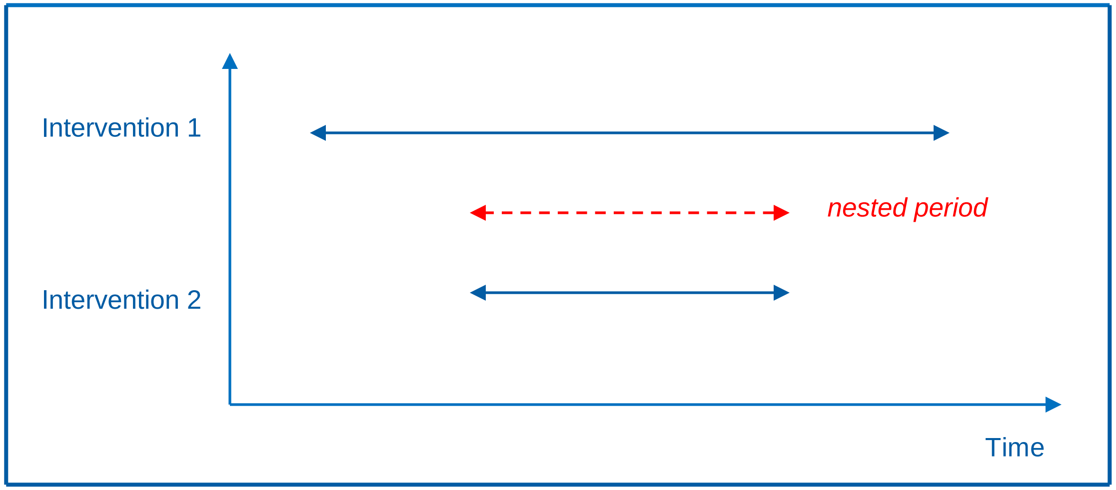
Overlapping and Nested Maintenance and Failure Records

The maintenance and failure records on an asset must not overlap and must not be nested for them to be modelled. Unfortunately, many databases have these problems because of the way the data were recorded.

The result of deduping a set of overlapping and nested maintenance interventions is one intervention that captures the true nature of the interventions and does not coincide with other interventions.

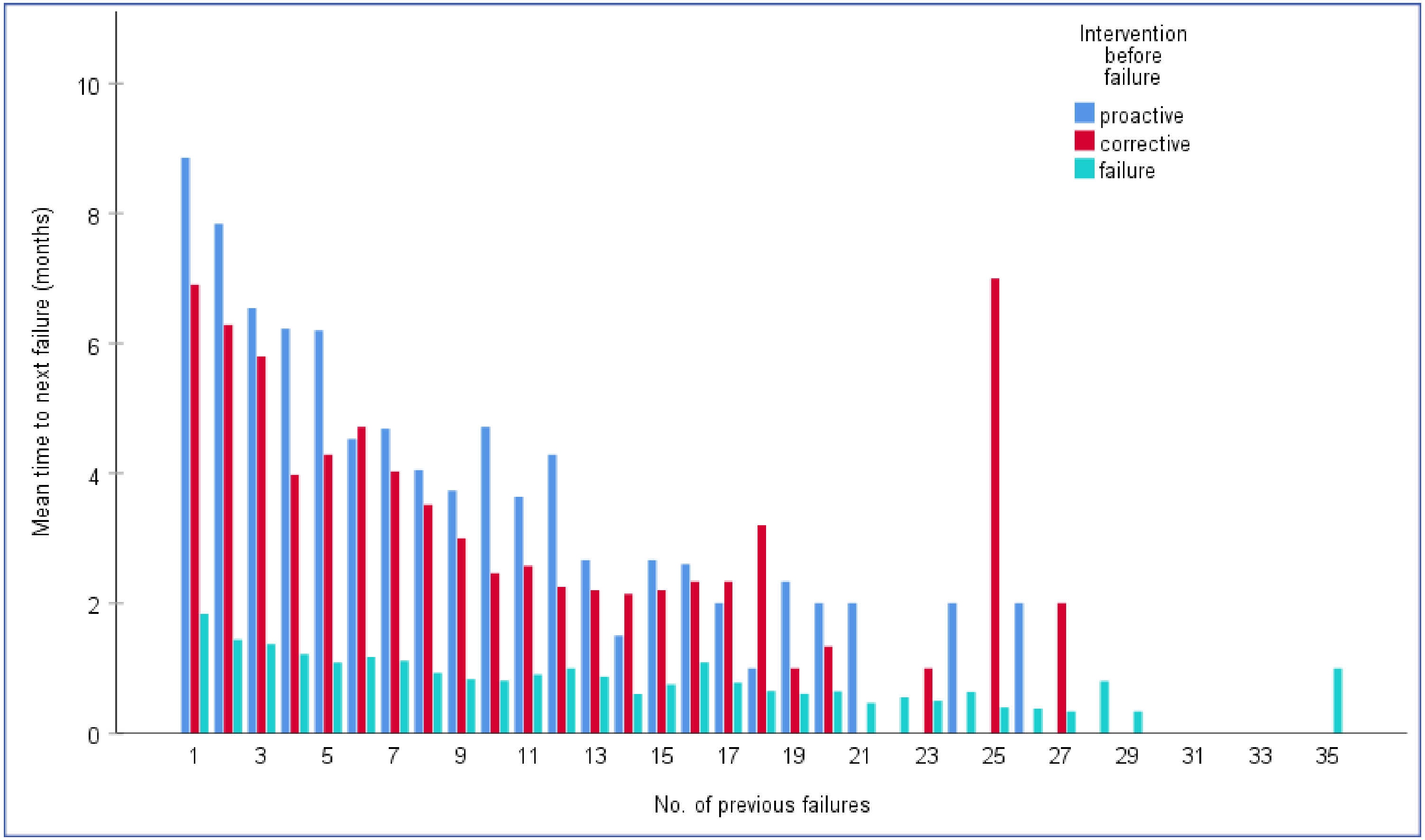
The level of overlapping and nesting determines the number of iterations required by the deduping algorithms.





PAM Asset Key Performance Indicators Module

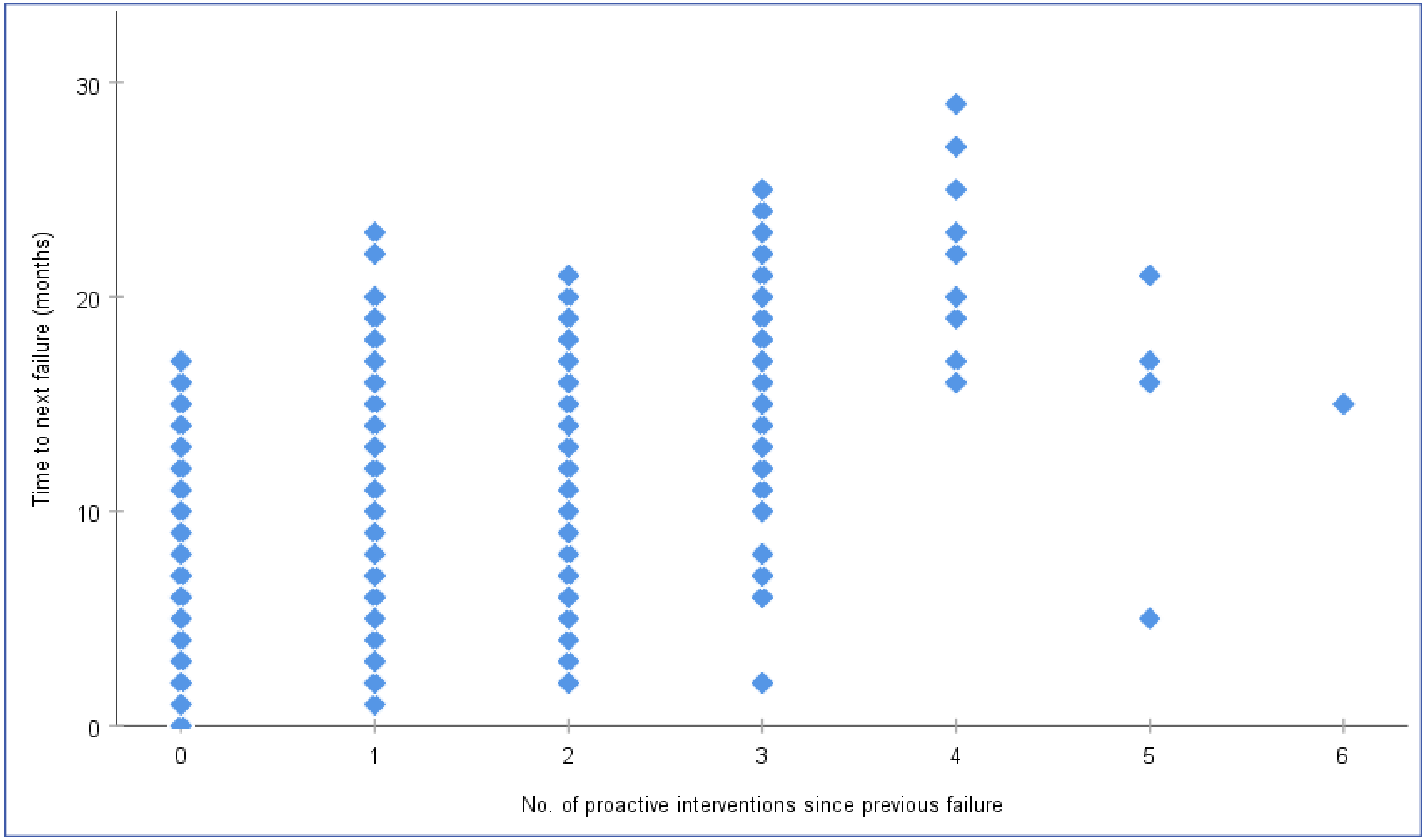
Dependence of Failure on Intervention History



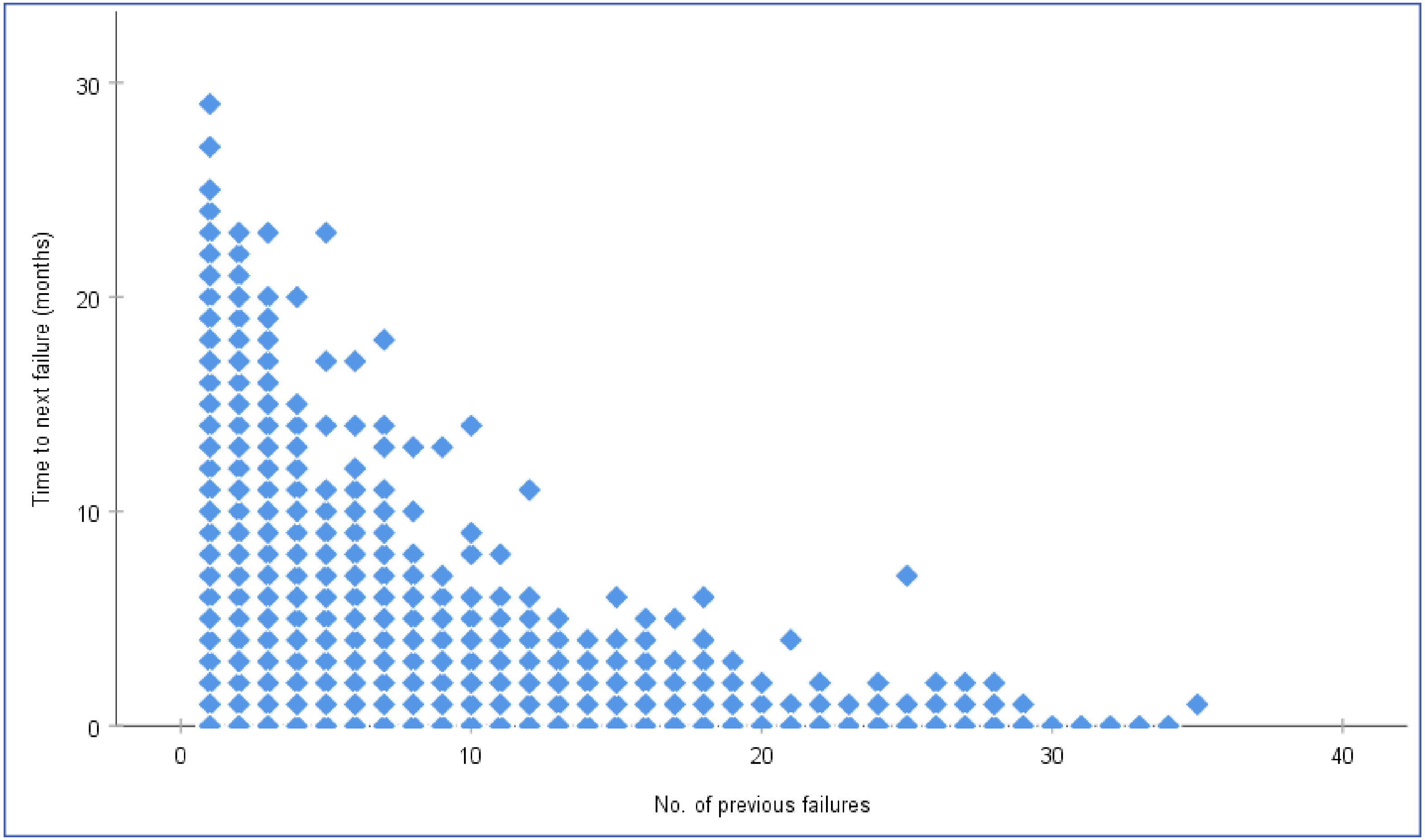
As the number of failures increases, the time from the most recent failure to the next failure decreases It is longest if the most recent intervention was proactive and shortest if it was a failure.

PAM Asset Key Performance Indicators Module

Dependence of Failure on Intervention History



As the number of proactive interventions after a failure increases, the time from the most recent failure to the next failure increases and tends to a limit.



As the number of failures increases, the time from the most recent failure to the next failure decreases rapidly.

PAM Predicted Maintenance Interventions Module

Example Survival Model (Wet Well Submersible Pumps)

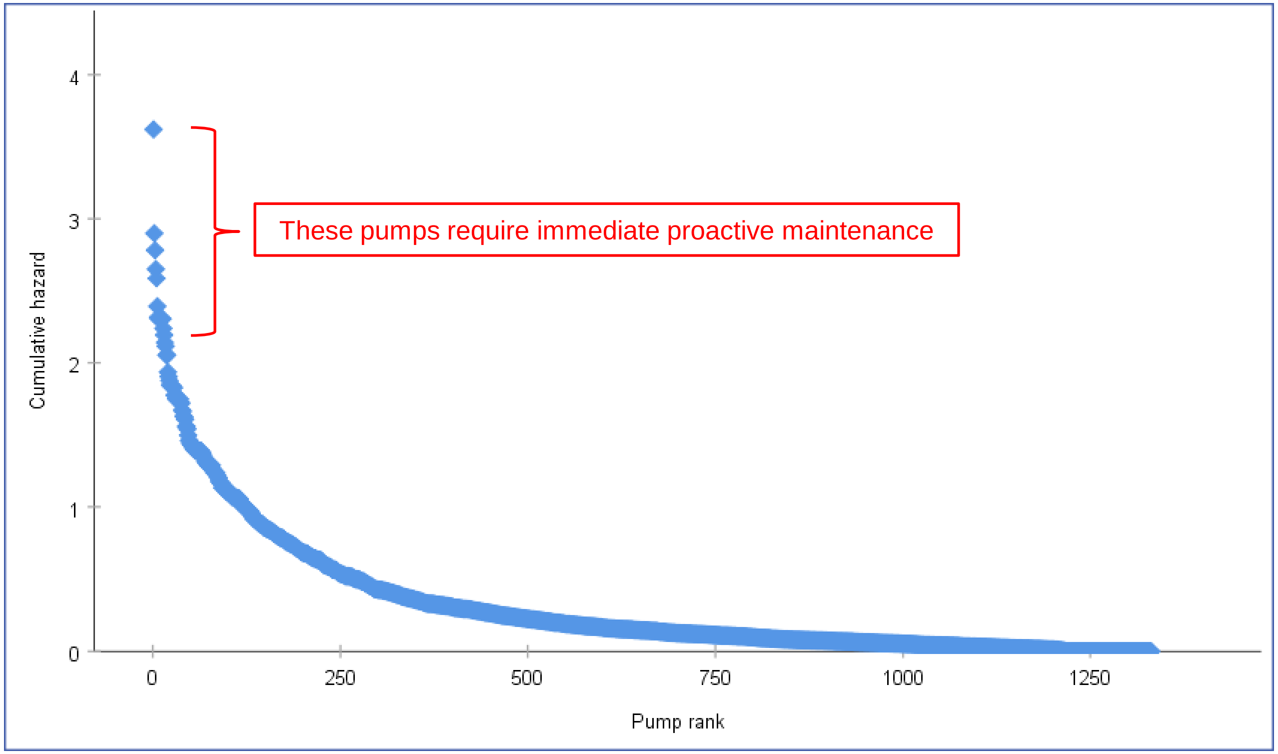
The target variable is the cumulative hazard of each pump at time *t.*

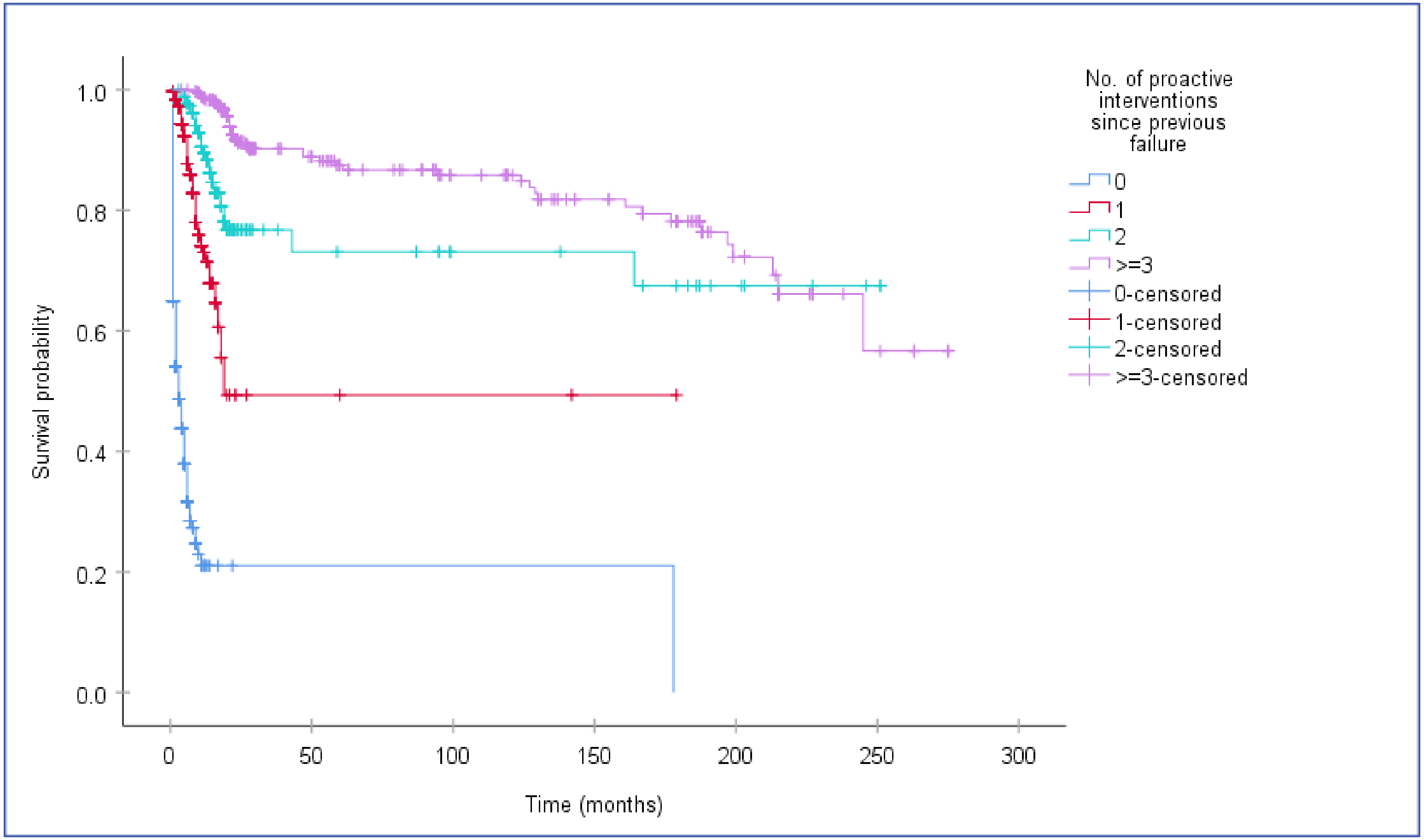
Predictor	Coefficient	Predictor	Coefficient
No. of proactive interventions: 0	3.884		
1	1.914	*Site postcode town:* postcode town *X*	0.230
2	0.914	other postcode towns	0
>=3	0		
No. of corrective interventions: 0	1.948		
1	0.460	*Maximum site pump power (kW)*: <=3	-0.287
>=2	0	>3	0
No. of previous failures: 0, 1	-1.236	*Monthly rainfall (mm)* <=150	-1.015
2, 3	-0.443	150 – 170	-0.467
>=4	0	>170	0
Mean no. of failures per year: <=0.1	-0.665		
0.1 – 0.5	-0.457	*Percent developed land*: <=10	-0.197
0.5 – 1	-0.205	>10	0
>1	0		
Population per site in each postcode district: <=400	0.312		
400 – 600	0.246		
>600	0		

Assets in Greatest Need of Proactive Maintenance

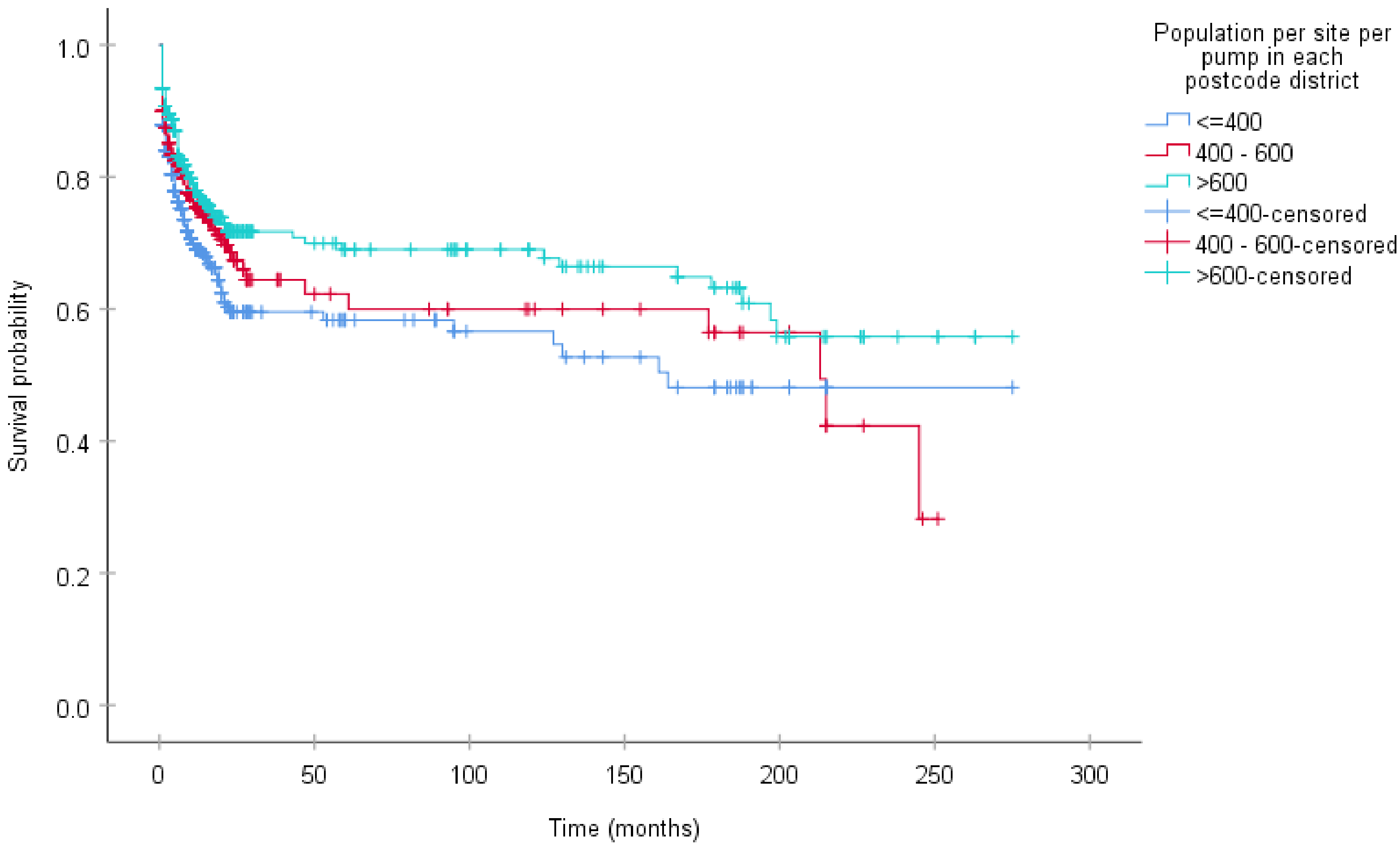
Pump Rank	Cumulative Hazard
1-50	1.44-3.62
51-100	1.11-1.44
101-150	0.86-1.10
151-200	0.68- 0.86
201-250	0.54-0.68

The range of the 50 largest cumulative hazards is 2.18 – this is over half the range of all the cumulative hazards but is accounted for by only 3.8% of the pumps. This leads to a highly skewed distribution of the cumulative hazard.

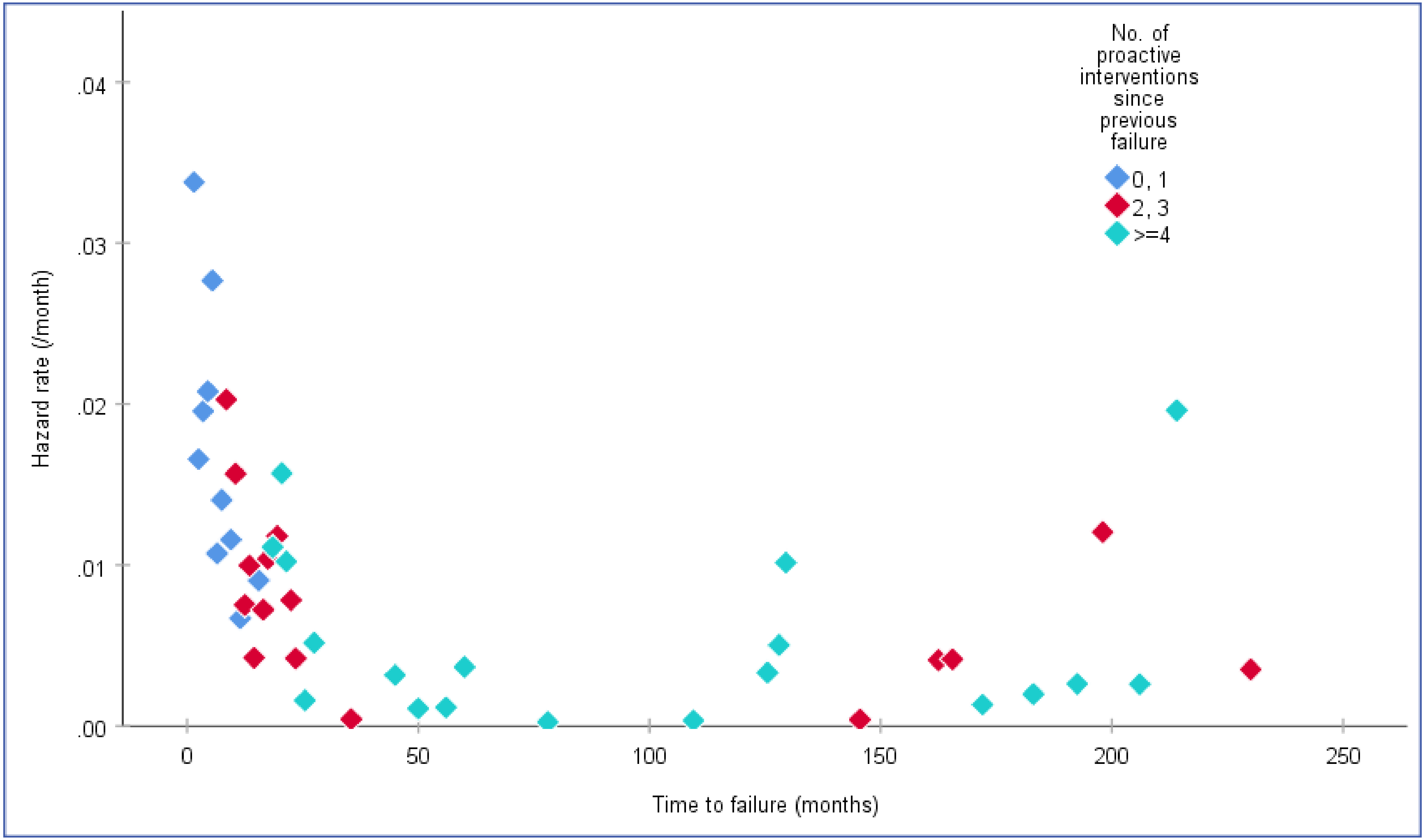




As the number of proactive interventions since the most recent failure increases, the survival probability and therefore the time to the next failure increase – as shown earlier.


Population per site per pump in each postcode district
<=400
400 - 600
>600
<=400-censored
400 - 600-censored
>600-censored
Survival probability
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
Time (months)

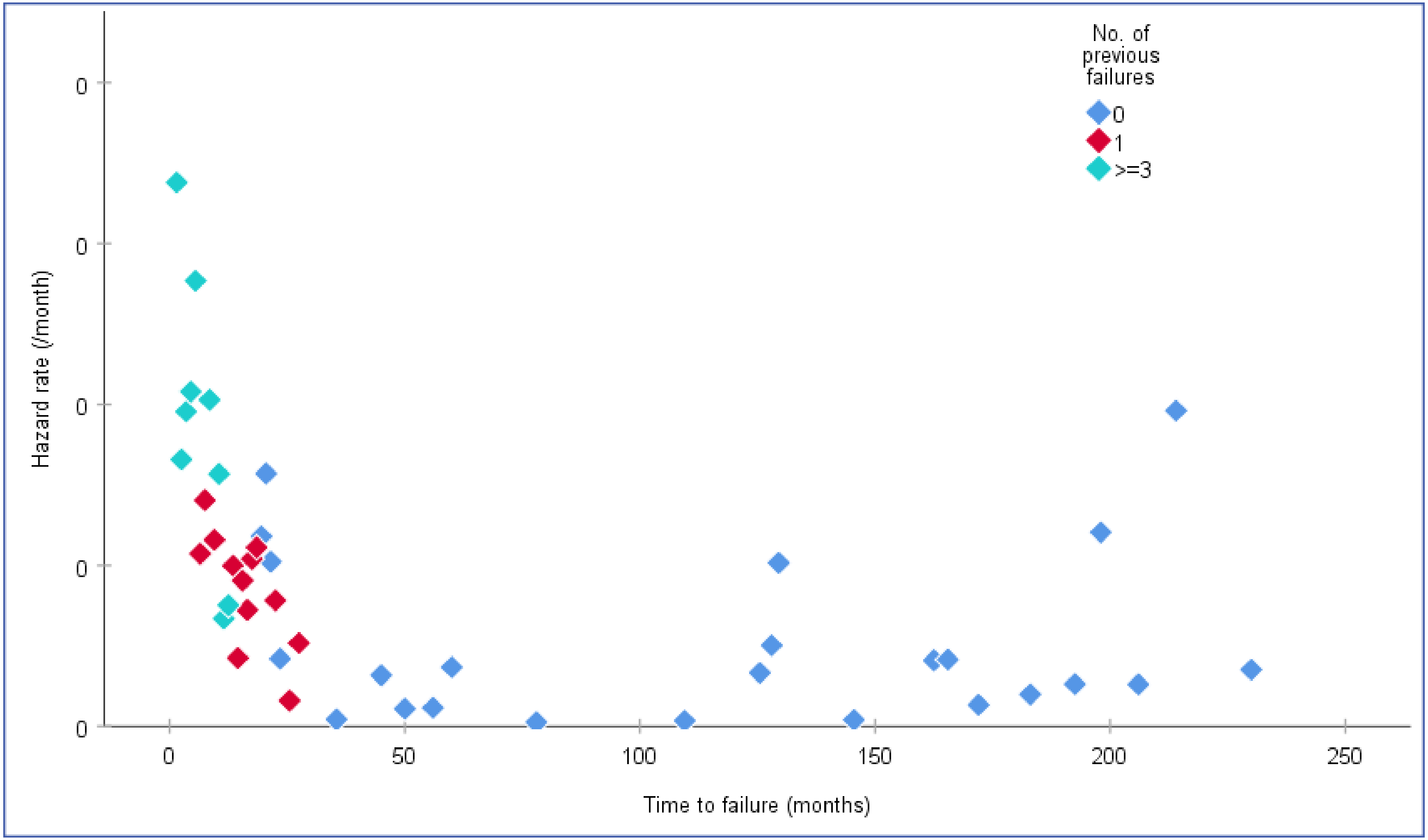
Hazard Rate Curve (calculated empirically)



PAM Analytics Predictive Asset Management

PAM Asset Deterioration Curves Module

Hazard Rate Curve (calculated empirically)



The Asset Survival Simulations module:

- optimises asset management at the strategic level with respect to the assets' maintenance and replacement costs, and any consequence costs resulting from asset failure
- carries out the optimisation heuristically by running penalty risk simulations of the financial implications each month of a range of asset maintenance and replacement policies to determine the optimal policy, i.e. the policy that minimises the penalty (the total asset management cost). The risk is the risk of repeated asset failure – this will ultimately lead to asset replacement.
- combines the survival models and discrete event simulation subject to constraints, for example the organisation's risk tolerance, i.e. attitude to the risk of asset failure, and maintenance capacity
- uses queueing algorithms to model the backlog of assets for maintenance or repair in the next simulation periods for assets that cannot have maintenance or be repaired in the current period.

Risk tolerance is:

- the maximum acceptable level of repeated asset failure
- the number of consecutive monthly failures an asset can have before it is replaced
- measured on a 5 point scale: 1 = risk averse; 5 = risk tolerant.

Risk tolerant asset management policies lead to lower asset maintenance costs than risk averse policies but result in higher asset replacement costs and consequence costs, and so lead to much higher total asset management costs than risk averse polices.

- Simulations for 2,250 pumps in wastewater pumping stations in 800 locations were carried out.
- The results are the total costs (proactive and reactive maintenance costs and the cost of replacement assets) for the next 5 years (the costs do not include the consequence costs of failure [which can be much greater than the pump related costs of failure]).

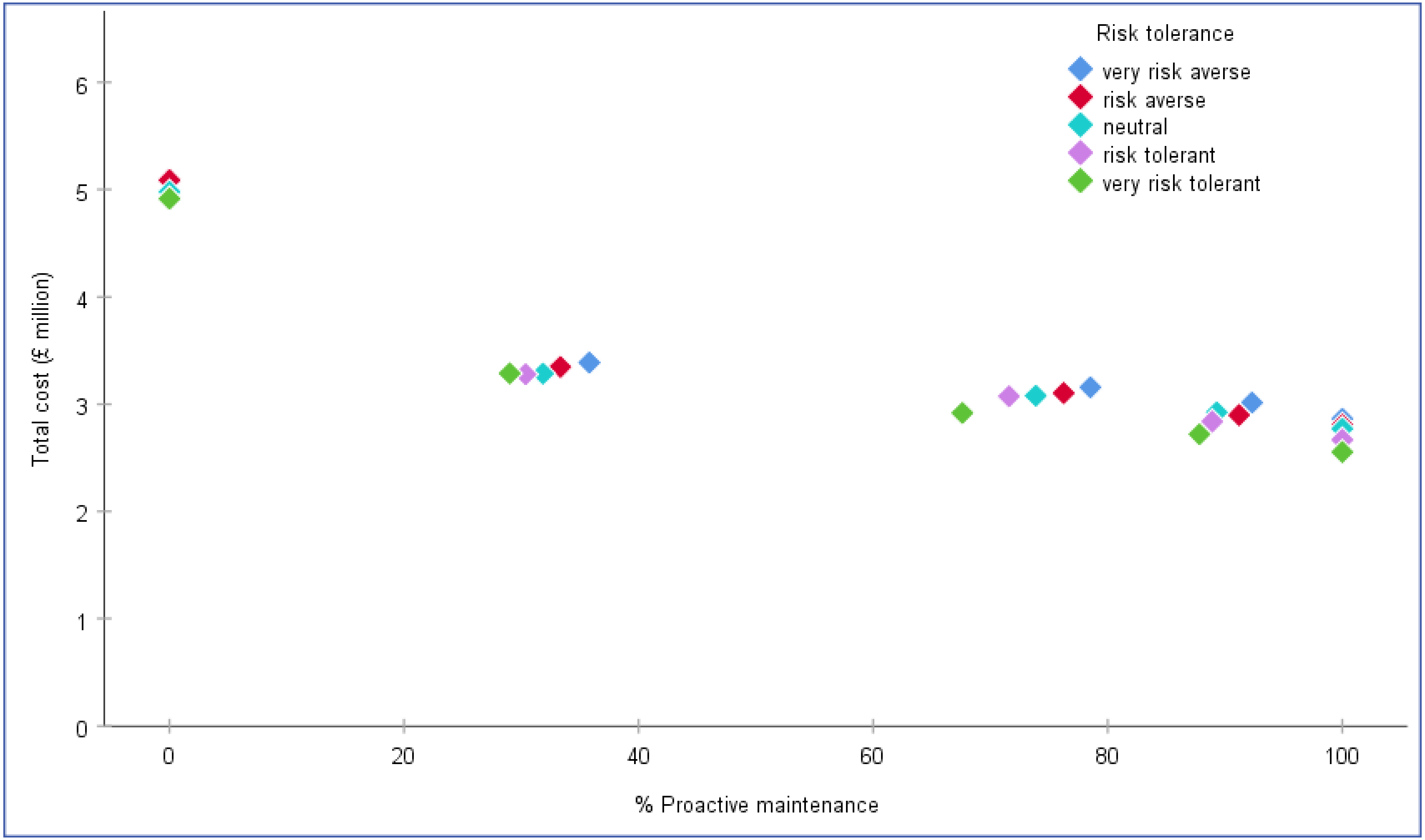
The input data are the (constant values are in red):

- maximum work capacity, i.e. the maximum number of proactive interventions and the maximum number of reactive interventions that can be carried out each month *
- number of consecutive monthly reactive interventions a pump can have for it to be deemed to have failed **
- threshold survival probability for proactive maintenance 0.20
- threshold survival probability for reactive maintenance 0.10
- cost of proactive maintenance and cost of reactive maintenance by pump class (and other factors)
- cost of replacement pumps
- interest rate 3%.

* maintenance capacity constraint

** risk tolerance constraint

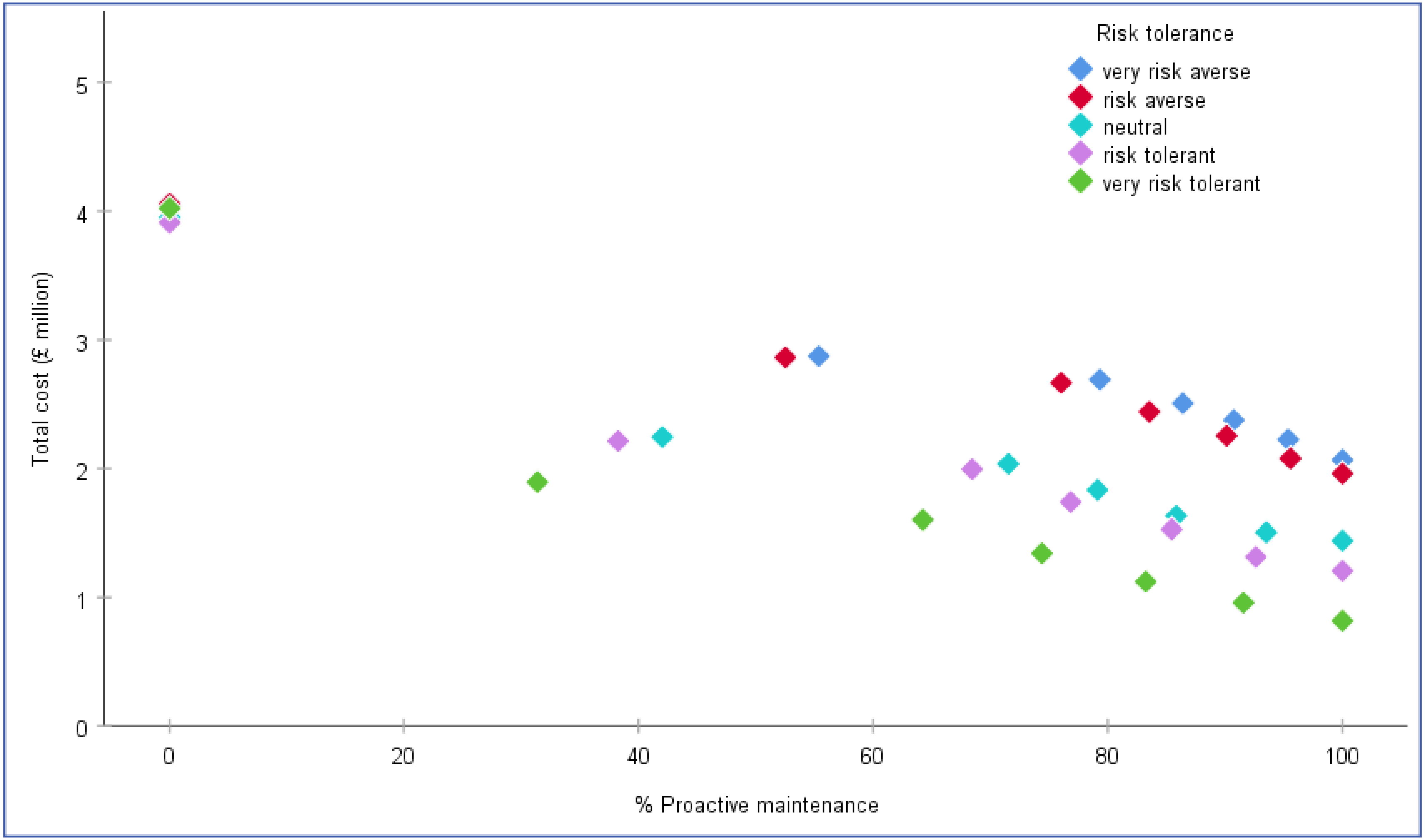
Low Maintenance Capacity (20 interventions per month)
Total Cost (proactive and reactive maintenance, and new pumps)



PAM Analytics Predictive Asset Management

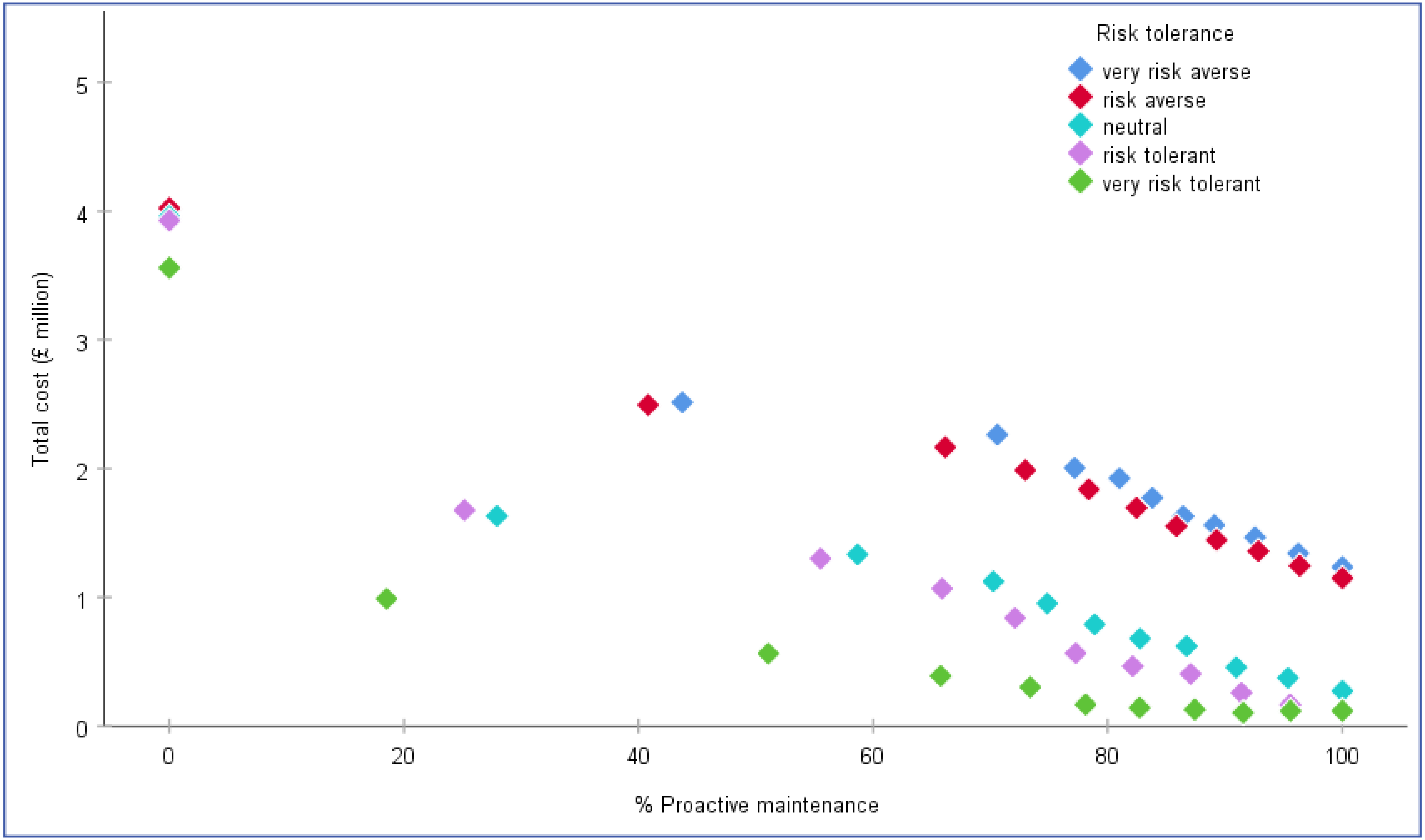
Medium Maintenance Capacity (60 interventions per month)

Total Cost (proactive and reactive maintenance, and new pumps)



High Maintenance Capacity (100 interventions per month)

Total Cost (proactive and reactive maintenance, and new pumps)



- The client selects one or two asset types of the same class, for example wet well submersible pumps, and prepares a sample of the data.

- PAM Analytics carries out a data quality audit and exploratory data analysis on the sample to gain a deep and thorough understanding of the data.
- This usually results in many questions about the data and may take a few iterations but its importance cannot be underestimated.

- PAM Analytics prepares the data for the analysis and modelling.
- PAM Analytics analyses and models the data.

- The deliverable is a report and presentation with results of the insight and understanding gained into asset performance and failure.

The work carried out in a PoC is required for a full PAM implementation and therefore does not have to be repeated.

Conclusion

PAM optimises asset management at individual asset level and at the operational, tactical and strategic levels by:

- changing the asset management policy from reactive fail-and-fix to proactive predict-and prevent
- allowing users to gain insight and understanding into asset performance and failure
- reducing the risk of asset failure, so increasing asset reliability and availability, and extending asset lifetimes
- reducing asset maintenance and replacement costs, and the consequence costs of asset failure.