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Progression of strategy optimisation

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Executive summary

This paper compares three variants of the common inspect and replace maintenance strategy, namely a fixed interval (inspect + replace), risk-based (inspect + replace), and adaptive (inspect + replace) strategy. The merits and shortcomings of each strategy variant are discussed and illustrated with a simple failure model. The failure model is comprised of a single failure mode and built of a lifetime distribution based on a wear out Weibull distribution. The optimum strategy is identified by comparing the total life cycle cost for each variant. The adaptive maintenance strategy delivered the lowest total life cycle cost by varying inspection intervals and identifying an optimum risk threshold. The fixed interval strategy delivered the worst results, illustrating the shortcomings of time invariant maintenance strategies. The risk-based strategy delivered close to optimum results, but the results are highly dependent on a business's ability to set an appropriate risk threshold.

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Contents

Acronyms

CMMS	Computerised Maintenance Management System
ERP	Enterprise Resource Planning
MTBF	Mean Time Between Failure
OEM	Original Equipment Manufacturer
RCM	Reliability Centred Maintenance

Abbreviations

P-F	Potential-to-Functional Failure

Symbols

β	Shape parameter
η	Characteristic life
γ	Failure free life

Definitions

Value framework: A value framework is a structured approach to decision making in complex environments. It provides a mechanism to trade off costs, risks and benefits to optimise the use of limited resources. Typically, a value framework consists of costs, risks, benefits and targets or KPI's / measures.

1 Introduction

The aim of the paper is to illustrate the thought progression of strategy optimisation by comparing simplified worked examples for common strategy options. The modelling methodology and chosen scenario do not form the focus of this paper. Similarly, the aim is not to identify or compare all maintenance strategies, but rather illustrate the benefits of adaptive and time variant strategies.

In response to the growing importance of understanding maintenance management, this paper evaluates three variants of an inspect and replace maintenance strategy by comparing total life cycle costs. The life cycle costs were calculated using a simple failure model built on a single failure mode.

Three variants of a typical inspection and secondary task strategy are modelled and optimised:

1. Fixed interval (inspect + replace)
2. Risk-based (inspect + replace)
3. Adaptive (inspect + replace)

2 Introduction to maintenance management

Historically, organisations have regarded maintenance activities with disdain labelling them as a necessary evil. Moreover, maintenance activities are a common item on the hit-list of cost-reductions exercises. However, recently maintenance has been recognised as a strategic issue by most organisations. The trend has largely been fuelled by toughening societal expectations such as environmental concerns and safety issues. New trends in operational strategies such as lean manufacturing and just-in-time production demand still more from maintenance programs.

The overall objective of maintenance management is to improve asset availability while reducing lifetime costs. Broadly any maintenance program can be classified as either corrective or preventative. Corrective programs are concerned with returning a failed asset to an operable condition. In comparison preventative programs describe maintenance activities carried out a regular interval intended to prevent or reduce the likelihood of failure.

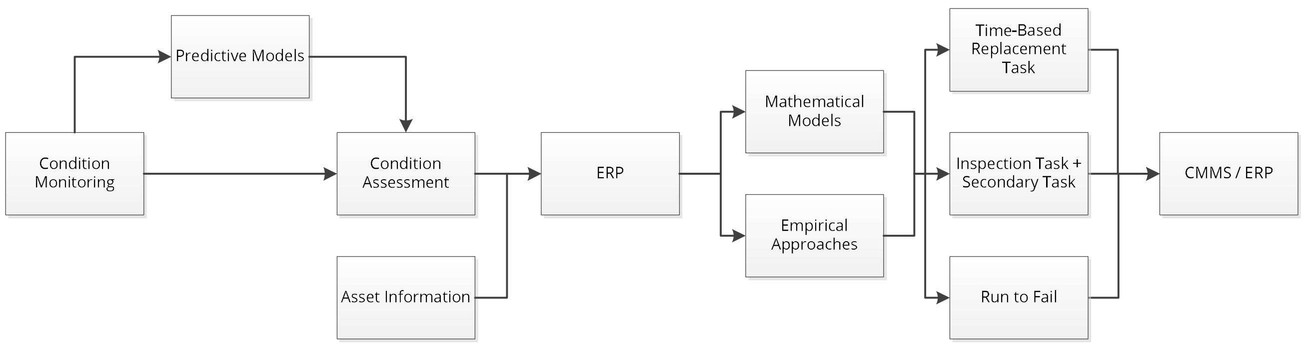

Figure 1: Maintenance management

Maintenance management encompasses more than corrective and inspection tasks. Figure 1 illustrates the functional silos that typically fall under maintenance management. Commonly preventative maintenance programs involve a form of condition monitoring. Condition monitoring includes visual inspections, sensory data and all other forms of condition observations. The outputs from condition monitoring feed into a condition assessment, either directly or via a predictive model.

Traditionally, condition monitoring outputs were mapped directly to a condition assessment, based on a predefined relationship. Predictive models have taken this one step further by incorporating machine learning models and producing real time condition assessments that can inform processes and trigger events.

The combination of condition assessments and asset information is fed into a methodology intended to produce an actionable maintenance strategy. Empirical approaches such as Reliability Centred Maintenance (RCM) identify failure modes that can affect the system, prioritise the failure modes, and select applicable and effective tasks to control the failure modes. This also involves modelling failures using mathematical models such as Weibull life distributions.

The result of this is an actionable maintenance strategy that can be broadly characterised as either:

1. Time-based replacement task
2. Inspection task + secondary task
3. Run to fail

A single asset can be maintained using any combination of the outlined strategies.

3 Modelling methodology

The objective of the failure model is to produce cost and risk profiles for each strategy variant. The failure model is representative of a single asset, characterised by a single failure mode. The failure model does not model replacement assets. Accordingly, the secondary task and consequence cost factors in the cost of replacement, but not the subsequent asset risk. The failure model is characterised by three separate cost measures:

1. Inspection costs: The cost of completing an inspection including all labour, materials and monetised risks.
2. Secondary costs: The cost incurred to replace the asset when an inspection has identified an imminent failure. Includes all labour, materials and monetised risks.
3. Consequence costs: The cost incurred to replace an asset reactively on failure. Includes all labour, materials and monetised risks.

Inspection tasks and their effectiveness are governed by a Potential-to-Functional Failure (P-F) interval and detection probability. The P-F interval is set up as a box interval for all scenarios, implying the probability of detection remains uniform across the entire window. The P-F interval is fixed at 5,110 hours with a detection probability of 80% for all scenarios.

For the single failure mode modelled, secondary actions result in a replacement and not refurbishment. Modelling replacements create a clear distinction between unique assets, allowing any resultant risk and cost implications following a replacement to be excluded from the model. Modelling refurbishments are more complex and not required to illustrate the main points of this paper.

By modelling replacements, the expected life of the modelled asset remains the same regardless of the inspection frequency. Therefore, the optimum frequency is determined as the lowest life cycle cost and cost to life ratio.

The model parameters common across the three variants are detailed in Table 1. The failure model is built of lifetime distributions based on a wear out Weibull distribution.

Table 1: Common model parameters

Parameter type	Parameter	Value
Project parameters	Project life	876,000 hours, or 0.999 CDF
Asset failure characteristics	η	87,600 hours
	β	3
	γ	0
	Initial age	0
Cost parameters	Inspection cost	$15,000 / inspection
	Secondary cost	$1,000,000
	Consequence cost	$5,000,000
Inspection parameters	P-F interval	5,110 hours
	Detection probability	80%

The risk and cost profiles are truncated at a point in time where the cumulative probability of failure reaches 0.999.

4 Modelled Scenarios

The simplest implementation of a preventive program comprises inspection tasks and accompanying secondary tasks. This paper models and compares three variants to determine optimal inspections timings that result in a minimum life cycle cost.

4.1 Fixed interval inspection + replace

This strategy schedules inspection tasks at a fixed periodic interval. Following an inspection, a corrective task such as a replacement is scheduled if a potential failure is found. Intervals can either be time based e.g. weekly or based on usage e.g. cycles or kilometres.

Optimisation of a time-based activity will converge on an interval that results in the lowest life cycle cost. This optimisation strategy is accompanied by the following advantages and disadvantages:

Advantages: Time based maintenance activities remain popular due to their ease of implementation. Moreover, Original Equipment Manufacturers (OEMs) typically provide time-based programs as a standard.

Disadvantages: New assets with a low probability of failure are inspected too often, and aging assets considered at risk are not inspected often enough. This results in periods of the asset's life where inspections can be wasted, or not cost beneficial, as well as periods where improvements can be made.

For the fixed interval strategy, 27 iterations including a run-to-fail scenario were modelled. The optimum inspection interval was found to be at 5,110 hours as shown in Table 2. Given a low inspection plus secondary to corrective cost ratio it can be expected that the optimum point would fall on or below the P-F interval.

Table 2: Fixed interval model overview

Optimised Interval (hours)	Total Lifetime Cost ($)	Number of Inspections	Cost Ratio
5,110	2,020,931	14.81	23.07

The cost contribution of inspections, secondary tasks and consequences of failure are evaluated in Figure 2. By including an uncertainty factor in the detection probability, consequence costs cannot be fully mitigated regardless of the inspection interval. As the modelled interval approaches the P-F interval, the combination of the inspection and consequence cost converges on a global minima. Past the P-F interval, as the inspection interval increases, the likelihood of undetected failures, and subsequent consequence cost increase proportionally.

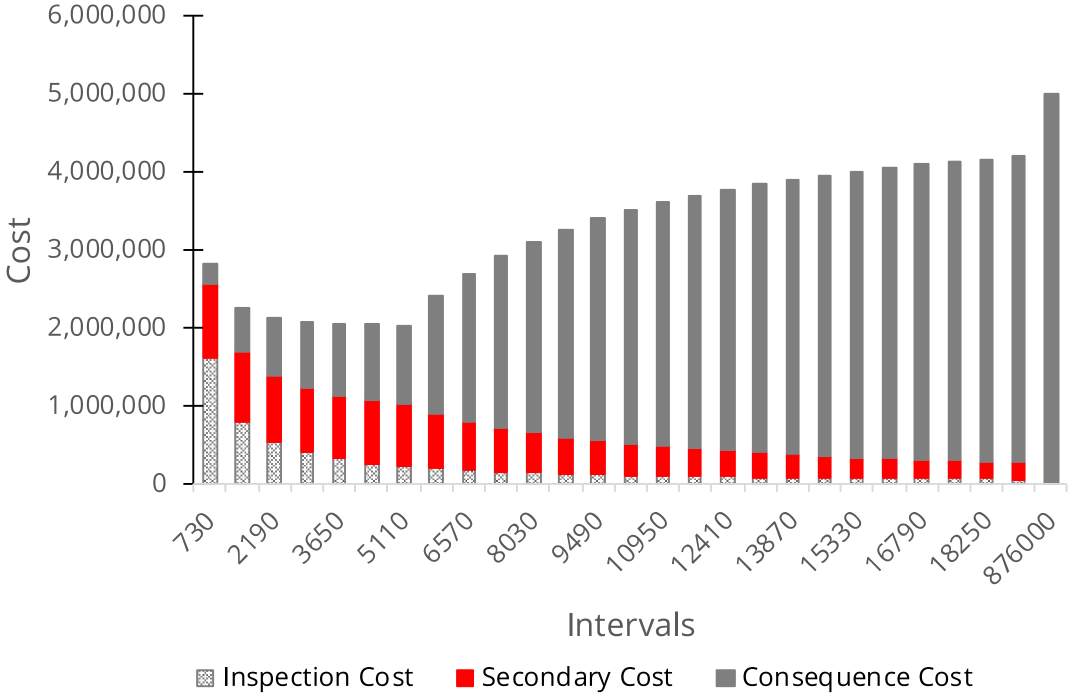

Figure 2: Cost composition of modelled fixed-time intervals

Figure 3 depicts the modelled inspection occurrences for the optimum interval of 5,110 hours. Over the modelled life cycle, 14.81 inspections are conducted. The part inspections are produced by factoring in the cumulative probability of failure. As an example; at 4,680 hours a near full inspection is modelled, as the probability that the asset has failed is very small, however, at 144,360 hours the probability that the asset has survived is very low, and correspondingly the probability of conducting an inspection is very low.

The validity of the inspection decay model is easily confirmed by comparing it to the total life inspections derived from the Mean Time Between Failure (MTBF) as shown in Eq 1 and Eq 2.

$$MTBF = \eta\left(\Gamma\left(\frac{1}{\beta}+1\right)\right)+\gamma = 78{,}225\ hours \qquad \textit{Eq 1}$$

$$Total\ life\ cycle\ inspection = \frac{MTBF}{Inspection\ interval} = 15.31\ inspections \qquad \textit{Eq 2}$$

The result is close to the analytical solution of 14.81.

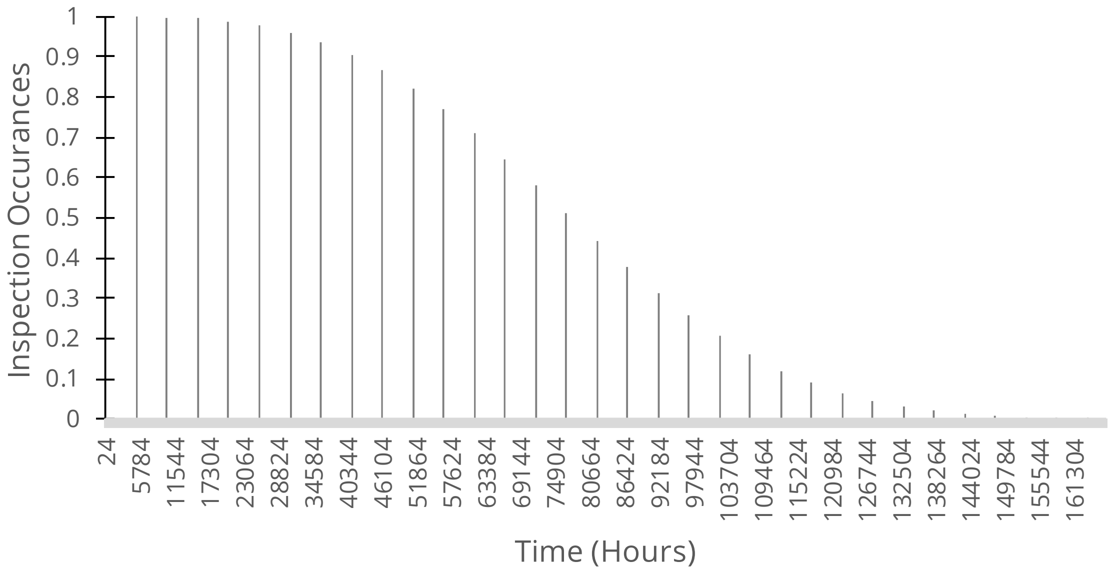

Figure 3: Inspection occurrences for an interval set at 5,110 hours

In Figure 4 the total number of life cycle inspections are plotted in comparison to the associated cost to life ratio. It illustrates how inspecting too frequently is cost inefficient as the increased frequency (below the P-F interval) does not materially reduce the risk. Conversely, by inspecting too infrequently any cost reduction related to reduced inspections are outweighed by the increased risk and subsequent consequence cost.

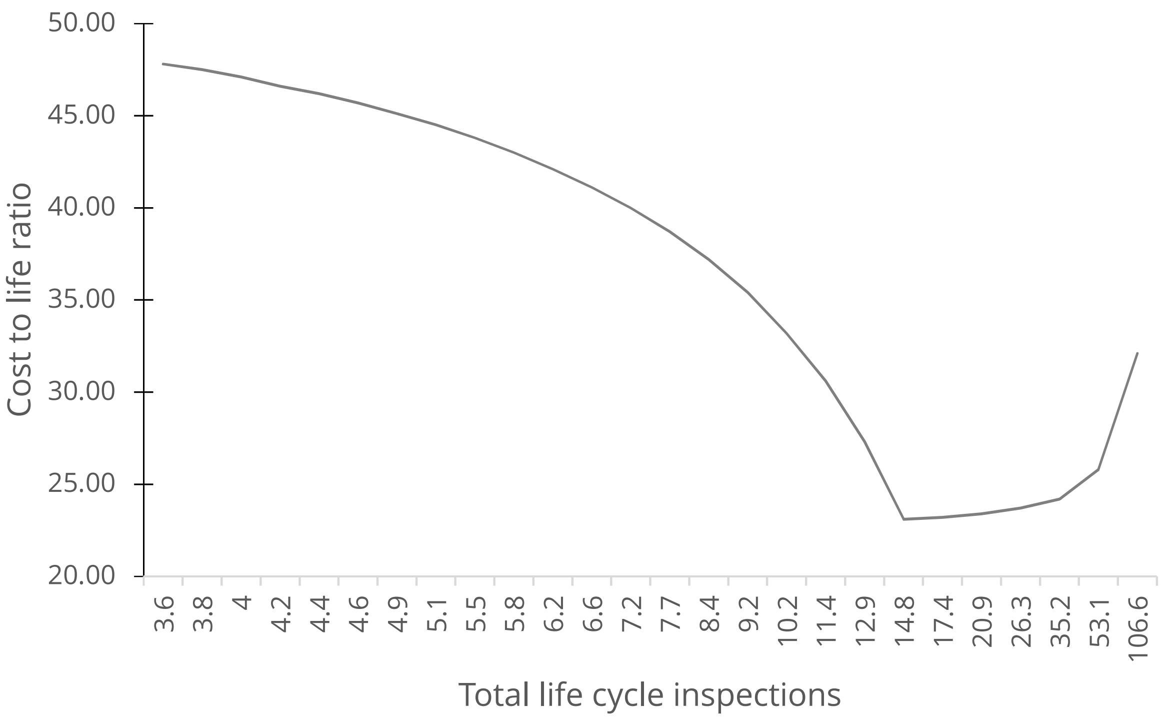

Figure 4: Cost to life ratio versus total life cycle inspections

As the methodology models replacements and the interval or number of inspections does not impact the characteristic life of the asset, Figure 4 is an exact mirror of Figure 3.

By plotting the relationship, it becomes apparent that a large range of intervals produce a near optimum cost to life ratio. The cost to life ratio at an inspection interval of 5,110 hours (≈15 life cycle inspections) is not materially different than at an inspection interval of 2,920 hours (≈26 life cycle inspections). The results from the complete optimisation exercise are detailed in Table 3.

Table 3: Fixed interval model results

Interval	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
730	106.65	1,599,694	946,615	261,923	2,808,231	32.06
1460	53.07	796,101	883,902	575,485	2,255,488	25.75
2190	35.22	528,236	849,795	746,022	2,124,053	24.25
2920	26.29	394,304	829,132	849,337	2,072,773	23.66
3650	20.93	313,936	815,120	919,394	2,048,451	23.39
4380	17.36	260,372	805,756	966,214	2,032,342	23.20
5110	14.81	222,097	799,041	999,793	2,020,931	23.07
5840	12.89	193,399	699,148	1,499,258	2,391,804	27.31
6570	11.41	171,079	621,434	1,887,823	2,680,337	30.60
7300	10.21	153,214	559,283	2,198,580	2,911,077	33.24
8030	9.24	138,605	508,447	2,452,762	3,099,814	35.39
8760	8.43	126,439	465,940	2,665,298	3,257,676	37.19
9490	7.74	116,130	430,264	2,843,675	3,390,069	38.70
10220	7.15	107,302	399,441	2,997,792	3,504,535	40.01
10950	6.64	99,650	372,757	3,131,211	3,603,618	41.14
11680	6.20	92,953	349,480	3,247,593	3,690,027	42.13
12410	5.80	87,042	329,019	3,349,903	3,765,964	43.00
13140	5.45	81,786	310,628	3,441,857	3,834,271	43.78
13870	5.14	77,094	294,093	3,524,530	3,895,717	44.48
14600	4.86	72,861	279,637	3,596,813	3,949,311	45.09
15330	4.60	69,026	266,098	3,664,504	3,999,629	45.66
16060	4.37	65,556	254,203	3,723,980	4,043,739	46.17
16790	4.16	62,369	242,877	3,780,610	4,085,856	46.65
17520	3.96	59,466	232,957	3,830,210	4,122,634	47.07
18250	3.79	56,791	223,495	3,877,523	4,157,808	47.47
18980	3.62	54,310	214,890	3,920,545	4,189,745	47.83

The subsequent modelled variant attempts to improve on the results obtained from the fixed interval optimisation by modelling time variant inspections.

4.2 Risk-based inspection + replace

The risk-based strategy schedules inspections based on the time variant risk level of the asset under consideration. A business sets a risk threshold calculated as shown in Eq 3

$$Risk = \ Probability\ of\ Failure * Consequence\ of\ Failure \qquad \text{Eq 3}$$

Once the modelled risk level reaches the defined threshold, an inspection is scheduled. The inspection will find potential failures and schedule a secondary task to address them. By identifying potential failures and eliminating them, the risk level is reduced for the duration of the P-F interval. As the asset ages, and the probability of failure increases faster, the risk level hits the threshold at increasingly frequent intervals. This results in a proportional increase in the number of scheduled inspections.

Advantages: A risk-based strategy addresses the deficiency of a fixed interval strategy by abandoning the rigidity of periodic tasks. This approach was introduced as a means for businesses to operate economically while managing risk to an acceptable level. Under the program, life cycle stages with a high degree of risk would warrant increased inspection tasks, while low risk stages would be managed in a limited manner. For example, an age-related failure mode on a new asset would be inspected at a reduced frequency initially and have the frequency gradually increase over time.

Disadvantages: The shortcoming of a risk-based strategy is contained in the setting of the risk threshold itself. The threshold is commonly set at a level, represented by a monetary value, that if exceeded poses irreparable or unacceptable risk to the business. The risk threshold does not seek to maximise the value gained by the business, only to remain within an upper limit. Thus, the threshold would typically not represent an optimal solution from an overall value standpoint.

Based on the modelled failure characteristics, the risk-based strategy should produce an improved cost to life ratio by delaying inspecting the new asset. This is however dependent on how close to the optimal point the risk threshold is set.

The mechanics of the risk-based strategy are well illustrated by Figure 5. The modelled threshold delays the first inspection as depicted by the rising consequence cost prior to hour 27,864. When the annualised risk hits the acceptable threshold, an inspection is performed. As the asset ages and the probability of failure grows faster, the inspections are scheduled more frequently.

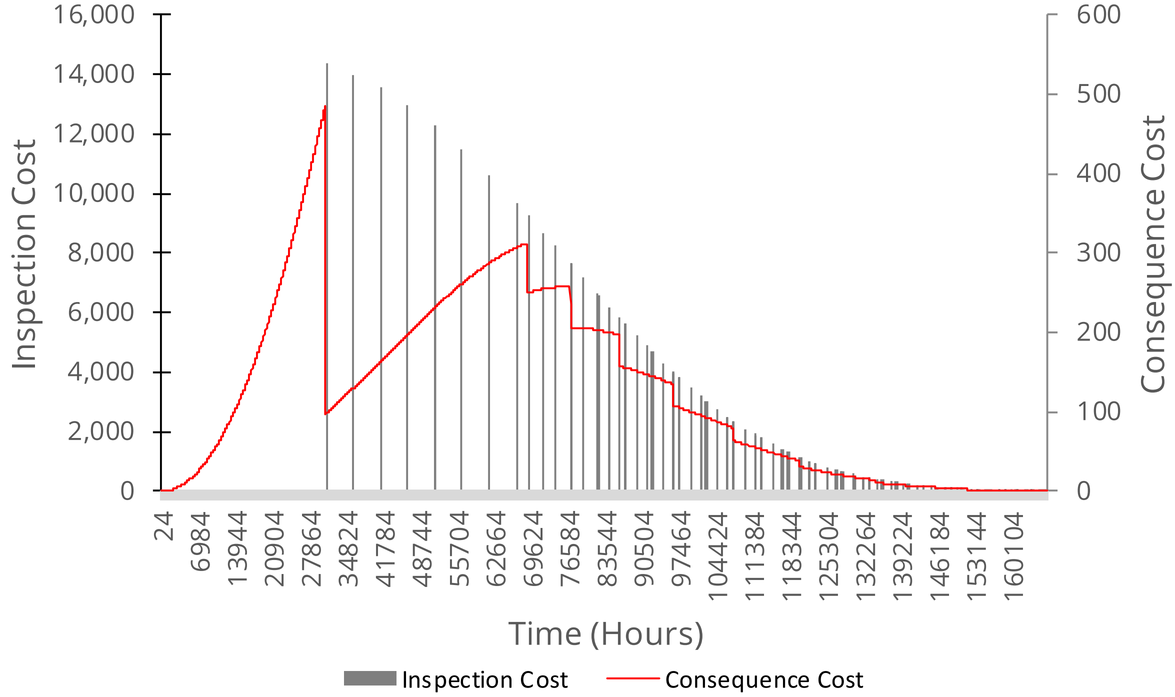

Figure 5: Inspection cost versus consequence cost for a risk-based approach

The risk-based scenario came in at $30,673 less than the optimum fixed interval, even with an additional ≈5 inspections. The approach produces lower consequence costs over an asset's life cycle as it shifts inspections towards an asset's most at risk years where they are of a greater cost benefit.

The results from the complete optimisation exercise are detailed in Table 4.

Table 4: Risk-based model overview

Threshold ($/annum)	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
185,000	19.78	296,648	825,347	868,263	1,990,258	22.72

The adaptive variation modelled in the subsequent section attempts to find a lower total lifecycle cost by varying the set risk threshold. A lower risk threshold could result in a reduced total lifecycle cost by constraining the probability of failure, or a higher risk threshold could reduce the inspection cost while maintaining a moderate consequence cost.

4.3 Adaptive inspection + replace

The adaptive strategy represents a natural progression of the risk-based strategy. It seeks to set the risk threshold at a level that optimises the value delivered by the maintenance program. The quality of the optimisation is dependent on how well the business understands and articulates risk consequences. If the business values safety, production and environmental aspects appropriately, an adaptive program will deliver a strategy that manages risk effectively and economically.

Advantages:	Removes the hard constraint of risk-based inspections, enabling identification of a lower life cycle cost.
Disadvantages:	The quality of the optimisation is dependent on the business's valuation of risk types. In practise the proposed strategy is typically overwritten if the perceived risk level is too high.

The optimisation attempts to improve on the risk-based strategy result by varying the risk threshold to see if a lower lifecycle cost option exists. If the consequence costs are correctly aligned with a business's value framework, the optimum threshold should produce an economically optimum result within tolerable risk levels. The results from the optimisation are detailed in Table 5. The full set of results can be found in Table 7 in Appendix 7.1. The cost to life ratio for each threshold computed in the optimisation are illustrated in Figure 6.

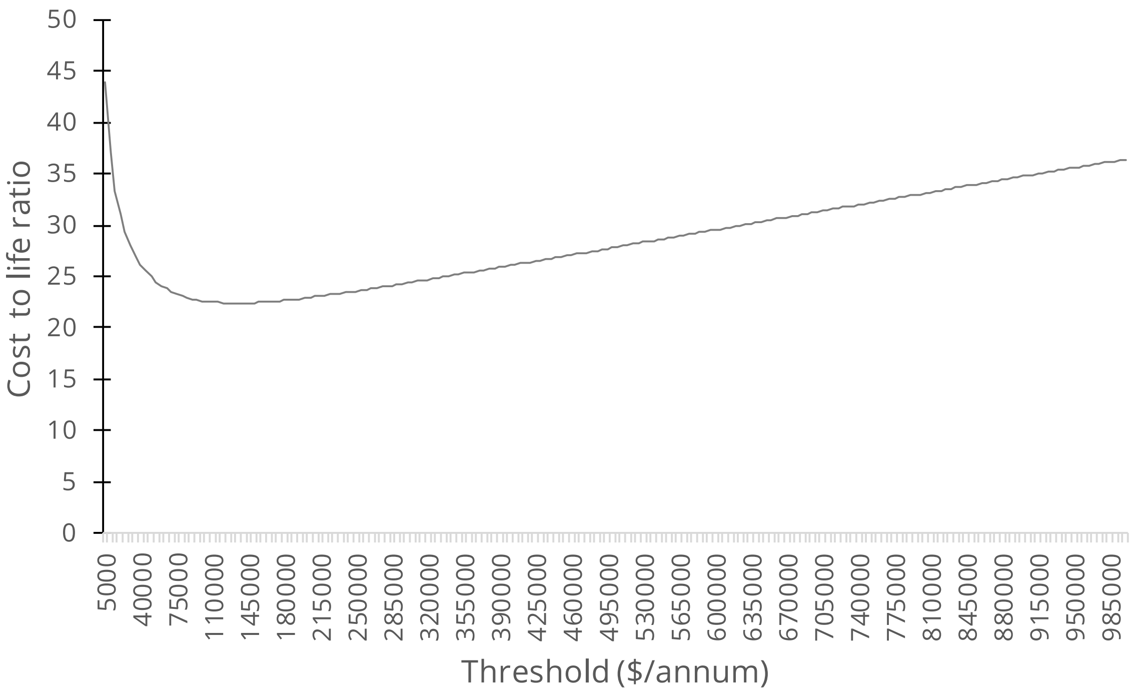

Figure 6: Cost to life ratio versus risk threshold

The adaptive strategy delivered a total lifetime cost of $1,962,363, $27,895 less than the risk-based strategy and $58,568 less than the fixed interval strategy. The values are of arbitrary importance as a different failure model with different failure characteristics would have produced vastly different results. However, regardless of the failure model parameters, the adaptive strategy will deliver more value than the fixed based strategy as it seeks to optimise the value delivered by the maintenance program.

Incremental improvements can be made on the fixed based strategy by modelling more intervals, however in reality, restrictive planning calendars would negate the gained value. The results from the complete adaptive optimisation exercise are detailed in Table 5

Table 5: Adaptive model results overview

Threshold ($/annum)	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
135,000	27.38	410,633	860,816	690,913	1,962,363	22.404

5 Comparison

The results from the three variants are tabulated in Table 6. The adaptive variant was best able to manage the risk by scheduling the largest number of inspections. However, the value of the approach lies in the timings of the inspections and not the quantity.

A fixed interval inspection of 2,920 hours resulted in a total of 26.29 inspections, similar to the adaptive strategy. However, the fixed interval inspections came at total cost of $2,072,772. This further illustrates that a time invariant strategy cannot produce the same value as a time variant strategy.

Table 6: Results comparison from the three modelled variations

Variation	Interval / Threshold	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
Fixed Interval	5,110	14.81	222,097	799,041	999,793	2,020,931	23.07
Risk-Based	185,000	19.78	296,648	825,347	868,263	1,990,258	22.72
Adaptive	135,000	27.38	410,633	860,816	690,913	1,962,363	22.40

6 Conclusion

The objective of the paper was to model the common fixed interval inspection and replace strategy and compare it to two alternatives. The modelling exercise showed that a risk-based and adaptive strategy can deliver superior maintenance programs that remain economical while managing risk within acceptable limits.

The successful implementation of an adaptive strategy hinges on a business's value framework and the quality thereof. But even with a robust value framework, businesses will struggle to implement time variant maintenance programs. Enterprise resource planning (ERP) solutions and Computerised Maintenance Management Systems (CMMSs) do not typically support the inclusion of time variant intervals. In addition, there are limited commercial solutions that can produce optimised maintenance programs from empirical approaches like RCM on bulk.

Successful and optimal maintenance programs should be focused on maximising value. Whether value is defined as reduced safety incidences or improved up-time, that is dependent on the business's value framework. An adaptive risk-based strategy illustrates one possible improvement to risk-based inspections whereby businesses can produce superior maintenance strategies, aligned with their key objectives and values.

7 Appendix

7.1 Adaptive strategy results

Table 7: Complete adaptive strategy results

Threshold ($/annum)	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
5,000	187.44	2,811,592	991,571	37,139	3,840,303	43.844
10,000	145.69	2,185,409	984,619	71,901	3,241,929	37.013
15,000	122.61	1,839,191	977,975	105,120	2,922,286	33.363
20,000	106.98	1,604,769	971,580	137,098	2,713,447	30.979
25,000	95.36	1,430,393	965,397	168,011	2,563,801	29.270
30,000	86.22	1,293,327	959,403	197,979	2,450,710	27.979
35,000	78.77	1,181,548	953,581	227,093	2,362,221	26.969
40,000	72.53	1,087,968	947,915	255,419	2,291,303	26.159
45,000	67.21	1,008,223	942,396	283,017	2,233,636	25.501
50,000	62.60	939,028	937,012	309,936	2,185,976	24.957
55,000	58.56	878,455	931,755	336,219	2,146,429	24.505
60,000	54.98	824,740	926,619	361,899	2,113,258	24.127
65,000	51.79	776,844	921,599	386,999	2,085,443	23.809
70,000	48.92	733,749	916,687	411,560	2,061,996	23.541
75,000	46.31	694,701	911,877	435,610	2,042,188	23.315
80,000	43.95	659,266	907,167	459,161	2,025,593	23.126
85,000	41.79	626,851	902,551	482,239	2,011,641	22.967
90,000	39.81	597,149	898,025	504,873	2,000,047	22.834
95,000	37.99	569,777	893,585	527,071	1,990,433	22.725
100,000	36.30	544,543	889,229	548,848	1,982,620	22.635
105,000	34.74	521,098	884,954	570,225	1,976,277	22.563
110,000	33.29	499,409	880,754	591,227	1,971,390	22.507
115,000	31.94	479,162	876,629	611,853	1,967,643	22.464
120,000	30.69	460,280	872,574	632,125	1,964,980	22.434
125,000	29.51	442,665	868,592	652,034	1,963,291	22.415
130,000	28.41	426,137	864,673	671,629	1,962,440	22.405
135,000	27.38	410,633	860,816	690,913	1,962,363	22.404
140,000	26.40	396,074	857,024	709,877	1,962,975	22.411
145,000	25.49	382,349	853,292	728,534	1,964,175	22.425
150,000	24.63	369,436	849,616	746,914	1,965,966	22.445
155,000	23.82	357,251	845,997	765,011	1,968,259	22.471
160,000	23.05	345,747	842,430	782,845	1,971,022	22.503
165,000	22.32	334,797	838,918	800,406	1,974,121	22.538
170,000	21.64	324,528	835,454	817,725	1,977,707	22.579
175,000	20.98	314,757	832,037	834,811	1,981,605	22.624
180,000	20.36	305,465	828,670	851,644	1,985,779	22.671

Threshold ($/annum)	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
185,000	19.78	296,648	825,347	868,263	1,990,258	22.722
190,000	19.22	288,282	822,069	884,652	1,995,003	22.777
195,000	18.69	280,327	818,836	900,818	1,999,980	22.833
200,000	18.18	272,745	815,642	916,785	2,005,172	22.893
205,000	17.70	265,477	812,485	932,568	2,010,530	22.954
210,000	17.24	258,622	809,371	948,141	2,016,133	23.018
215,000	16.80	252,045	806,291	963,539	2,021,875	23.083
220,000	16.38	245,763	803,246	978,766	2,027,775	23.151
225,000	15.98	239,766	800,238	993,803	2,033,808	23.220
230,000	15.60	233,999	797,264	1,008,677	2,039,940	23.290
235,000	15.23	228,525	794,323	1,023,382	2,046,229	23.361
240,000	14.88	223,271	791,413	1,037,928	2,052,613	23.434
245,000	14.55	218,251	788,536	1,052,318	2,059,104	23.508
250,000	14.23	213,436	785,688	1,066,558	2,065,682	23.584
255,000	13.92	208,774	782,866	1,080,668	2,072,308	23.659
260,000	13.62	204,351	780,074	1,094,624	2,079,049	23.736
265,000	13.34	200,114	777,308	1,108,457	2,085,879	23.814
270,000	13.07	196,014	774,566	1,122,167	2,092,746	23.893
275,000	12.81	192,086	771,847	1,135,758	2,099,692	23.972
280,000	12.55	188,299	769,158	1,149,206	2,106,663	24.051
285,000	12.31	184,655	766,492	1,162,537	2,113,684	24.132
290,000	12.08	181,161	763,845	1,175,771	2,120,777	24.213
295,000	11.85	177,781	761,221	1,188,893	2,127,894	24.294
300,000	11.64	174,528	758,623	1,201,882	2,135,033	24.375
305,000	11.43	171,418	756,037	1,214,809	2,142,264	24.458
310,000	11.23	168,405	753,477	1,227,609	2,149,492	24.540
315,000	11.03	165,496	750,934	1,240,328	2,156,758	24.623
320,000	10.84	162,649	748,411	1,252,940	2,164,000	24.706
325,000	10.66	159,958	745,904	1,265,477	2,171,339	24.790
330,000	10.49	157,355	743,410	1,277,943	2,178,709	24.874
335,000	10.32	154,840	740,937	1,290,309	2,186,086	24.958
340,000	10.16	152,383	738,485	1,302,572	2,193,440	25.042
345,000	10.00	150,002	736,040	1,314,794	2,200,837	25.127
350,000	9.85	147,716	733,615	1,326,920	2,208,252	25.211
355,000	9.70	145,502	731,203	1,338,979	2,215,684	25.296
360,000	9.56	143,356	728,801	1,350,993	2,223,149	25.381
365,000	9.42	141,292	726,416	1,362,915	2,230,623	25.467
370,000	9.28	139,264	724,045	1,374,769	2,238,078	25.552
375,000	9.15	137,312	721,686	1,386,564	2,245,563	25.637
380,000	9.03	135,433	719,340	1,398,298	2,253,070	25.723
385,000	8.91	133,579	717,005	1,409,972	2,260,556	25.808

Threshold ($/annum)	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
390,000	8.79	131,810	714,682	1,421,585	2,268,077	25.894
395,000	8.67	130,062	712,371	1,433,140	2,275,572	25.980
400,000	8.56	128,362	710,066	1,444,668	2,283,096	26.066
405,000	8.45	126,741	707,771	1,456,140	2,290,652	26.152
410,000	8.34	125,165	705,488	1,467,555	2,298,208	26.238
415,000	8.24	123,632	703,217	1,478,912	2,305,761	26.324
420,000	8.14	122,109	700,950	1,490,247	2,313,306	26.411
425,000	8.04	120,657	698,694	1,501,528	2,320,879	26.497
430,000	7.95	119,212	696,441	1,512,788	2,328,441	26.583
435,000	7.86	117,835	694,200	1,523,994	2,336,030	26.670
440,000	7.77	116,481	691,970	1,535,144	2,343,596	26.756
445,000	7.68	115,173	689,744	1,546,277	2,351,194	26.843
450,000	7.59	113,884	687,529	1,557,350	2,358,763	26.930
455,000	7.51	112,640	685,318	1,568,403	2,366,362	27.016
460,000	7.43	111,397	683,118	1,579,405	2,373,921	27.103
465,000	7.35	110,199	680,921	1,590,391	2,381,510	27.189
470,000	7.27	109,042	678,727	1,601,359	2,389,129	27.276
475,000	7.19	107,898	676,543	1,612,278	2,396,719	27.363
480,000	7.12	106,778	674,363	1,623,182	2,404,323	27.450
485,000	7.05	105,700	672,193	1,634,033	2,411,926	27.537
490,000	6.98	104,644	670,025	1,644,871	2,419,540	27.623
495,000	6.91	103,596	667,860	1,655,695	2,427,151	27.710
500,000	6.84	102,558	665,706	1,666,467	2,434,730	27.797
505,000	6.77	101,568	663,547	1,677,262	2,442,377	27.884
510,000	6.71	100,600	661,398	1,688,006	2,450,004	27.971
515,000	6.64	99,653	659,260	1,698,698	2,457,611	28.058
520,000	6.58	98,722	657,116	1,709,416	2,465,253	28.145
525,000	6.52	97,781	654,983	1,720,081	2,472,845	28.232
530,000	6.46	96,886	652,845	1,730,773	2,480,503	28.319
535,000	6.40	96,009	650,717	1,741,412	2,488,138	28.407
540,000	6.34	95,120	648,592	1,752,038	2,495,750	28.494
545,000	6.29	94,280	646,477	1,762,611	2,503,367	28.581
550,000	6.23	93,451	644,357	1,773,211	2,511,019	28.668
555,000	6.18	92,639	642,248	1,783,757	2,518,644	28.755
560,000	6.12	91,823	640,134	1,794,326	2,526,284	28.842
565,000	6.07	91,039	638,032	1,804,838	2,533,908	28.929
570,000	6.02	90,266	635,924	1,815,377	2,541,567	29.017
575,000	5.97	89,478	633,827	1,825,863	2,549,167	29.103
580,000	5.91	88,704	631,732	1,836,336	2,556,771	29.190
585,000	5.86	87,970	629,632	1,846,837	2,564,439	29.278
590,000	5.82	87,249	627,542	1,857,284	2,572,076	29.365

Threshold ($/annum)	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
595,000	5.77	86,540	625,456	1,867,716	2,579,712	29.452
600,000	5.72	85,839	623,363	1,878,178	2,587,381	29.540
605,000	5.68	85,150	621,282	1,888,583	2,595,016	29.627
610,000	5.63	84,472	619,204	1,898,974	2,602,651	29.714
615,000	5.59	83,786	617,120	1,909,394	2,610,300	29.801
620,000	5.54	83,129	615,048	1,919,754	2,617,931	29.888
625,000	5.50	82,449	612,970	1,930,144	2,625,563	29.976
630,000	5.45	81,809	610,895	1,940,519	2,633,223	30.063
635,000	5.41	81,177	608,823	1,950,878	2,640,879	30.150
640,000	5.37	80,554	606,755	1,961,221	2,648,531	30.238
645,000	5.33	79,940	604,689	1,971,548	2,656,178	30.325
650,000	5.29	79,333	602,627	1,981,859	2,663,820	30.412
655,000	5.25	78,720	600,569	1,992,152	2,671,441	30.499
660,000	5.21	78,128	598,504	2,002,474	2,679,106	30.587
665,000	5.17	77,546	596,453	2,012,733	2,686,731	30.674
670,000	5.13	76,969	594,395	2,023,019	2,694,383	30.761
675,000	5.09	76,370	592,342	2,033,287	2,701,999	30.848
680,000	5.05	75,807	590,283	2,043,581	2,709,671	30.936
685,000	5.02	75,253	588,237	2,053,811	2,717,301	31.023
690,000	4.98	74,703	586,186	2,064,068	2,724,956	31.110
695,000	4.94	74,145	584,138	2,074,305	2,732,588	31.198
700,000	4.91	73,594	582,096	2,084,515	2,740,205	31.284
705,000	4.87	73,064	580,059	2,094,703	2,747,826	31.371
710,000	4.84	72,539	578,016	2,104,917	2,755,472	31.459
715,000	4.80	72,022	575,986	2,115,064	2,763,072	31.546
720,000	4.77	71,492	573,943	2,125,283	2,770,717	31.633
725,000	4.73	70,970	571,913	2,135,433	2,778,315	31.720
730,000	4.70	70,467	569,877	2,145,609	2,785,954	31.807
735,000	4.66	69,970	567,847	2,155,762	2,793,579	31.894
740,000	4.63	69,479	565,821	2,165,893	2,801,192	31.981
745,000	4.60	68,992	563,799	2,176,000	2,808,791	32.068
750,000	4.57	68,509	561,773	2,186,130	2,816,413	32.155
755,000	4.54	68,031	559,752	2,196,237	2,824,020	32.241
760,000	4.50	67,556	557,726	2,206,367	2,831,649	32.328
765,000	4.47	67,088	555,715	2,216,423	2,839,226	32.415
770,000	4.44	66,607	553,689	2,226,551	2,846,847	32.502
775,000	4.41	66,147	551,678	2,236,604	2,854,430	32.589
780,000	4.38	65,691	549,663	2,246,679	2,862,033	32.675
785,000	4.35	65,225	547,654	2,256,727	2,869,606	32.762
790,000	4.32	64,778	545,650	2,266,748	2,877,176	32.848
795,000	4.29	64,334	543,641	2,276,790	2,884,765	32.935

Threshold ($/annum)	Total Inspections	Total Inspection Cost ($)	Total Secondary Cost ($)	Total Consequence Cost ($)	Total Cost ($)	Cost to Life Ratio
800,000	4.26	63,895	541,639	2,286,803	2,892,336	33.021
805,000	4.23	63,458	539,632	2,296,837	2,899,927	33.108
810,000	4.20	63,025	537,631	2,306,842	2,907,498	33.194
815,000	4.17	62,597	535,636	2,316,817	2,915,049	33.281
820,000	4.14	62,141	533,637	2,326,812	2,922,590	33.367
825,000	4.11	61,721	531,644	2,336,776	2,930,140	33.453
830,000	4.09	61,302	529,647	2,346,759	2,937,708	33.539
835,000	4.06	60,888	527,657	2,356,710	2,945,255	33.625
840,000	4.03	60,463	525,673	2,366,630	2,952,766	33.711
845,000	4.00	60,055	523,686	2,376,567	2,960,308	33.797
850,000	3.98	59,652	521,705	2,386,472	2,967,828	33.883
855,000	3.95	59,250	519,720	2,396,394	2,975,364	33.969
860,000	3.92	58,852	517,743	2,406,282	2,982,877	34.055
865,000	3.90	58,456	515,762	2,416,187	2,990,405	34.141
870,000	3.87	58,064	513,788	2,426,057	2,997,909	34.227
875,000	3.84	57,662	511,822	2,435,884	3,005,368	34.312
880,000	3.82	57,276	509,854	2,445,726	3,012,856	34.397
885,000	3.79	56,894	507,893	2,455,533	3,020,320	34.482
890,000	3.77	56,514	505,928	2,465,355	3,027,797	34.568
895,000	3.74	56,137	503,971	2,475,141	3,035,249	34.653
900,000	3.72	55,748	502,011	2,484,942	3,042,700	34.738
905,000	3.69	55,377	500,058	2,494,705	3,050,140	34.823
910,000	3.67	55,008	498,103	2,504,483	3,057,594	34.908
915,000	3.64	54,642	496,155	2,514,222	3,065,020	34.993
920,000	3.62	54,278	494,204	2,523,975	3,072,458	35.078
925,000	3.59	53,918	492,261	2,533,689	3,079,868	35.162
930,000	3.57	53,559	490,316	2,543,416	3,087,291	35.247
935,000	3.55	53,203	488,379	2,553,103	3,094,685	35.332
940,000	3.52	52,849	486,439	2,562,802	3,102,090	35.416
945,000	3.50	52,498	484,507	2,572,460	3,109,466	35.500
950,000	3.48	52,149	482,573	2,582,130	3,116,852	35.585
955,000	3.45	51,789	480,647	2,591,759	3,124,195	35.668
960,000	3.43	51,432	478,730	2,601,345	3,131,507	35.752
965,000	3.41	51,090	476,800	2,610,994	3,138,884	35.836
970,000	3.38	50,751	474,879	2,620,601	3,146,231	35.920
975,000	3.36	50,415	472,966	2,630,165	3,153,547	36.004
980,000	3.34	50,081	471,051	2,639,739	3,160,871	36.087
985,000	3.32	49,750	469,146	2,649,268	3,168,164	36.170
990,000	3.29	49,421	467,238	2,658,806	3,175,465	36.254
995,000	3.27	49,092	465,329	2,668,353	3,182,774	36.337
1000,000	3.25	48,767	463,428	2,677,855	3,190,050	36.420

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