TESIS DOCTORAL

COMPENDIO DE PUBLICACIONES

PROPUESTA DE HERRAMIENTAS GRÁFICAS PARA EL DIAGNÓSTICO, ANÁLISIS Y CONTROL DE GESTIÓN EN MANTENIMIENTO Y PRODUCCIÓN, INCORPORANDO INDICADORES FUNDAMENTALES DE FIABILIDAD Y RENDIMIENTO

DOCTORADO EN INGENIERÍA MECÁNICA Y DE ORGANIZACIÓN INDUSTRIAL

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1. INTRODUCCIÓN

La medición del rendimiento (performance) corresponde al proceso de cuantificación de una acción, donde específicamente la "medición" es el proceso de cuantificación, y la "acción" es la materialización objetiva de una actividad realizada (Nelly, 1995). Los conceptos de eficiencia y efectividad se utilizan precisamente en este contexto, donde la efectividad se refiere a la medida en que se cumplen los objetivos definidos para el proceso, mientras que la eficiencia es una medida de economía en la cual los recursos son utilizados para cumplir los objetivos establecidos (Koontz and Weihrich, 2003). Bajo este contexto entonces, existe una estrecha relación entre el control de gestión a través de indicadores de desempeño (KPI[1]), la definición de estrategias y la toma de decisiones en todas sus dimensiones (Guillemette et al., 2014; Chai et al., 2013).

Existen diferentes propuestas para el diseño de sistemas de medición y control, donde la mayor parte de estas convergen en el hecho que para el éxito en su diseño, implementación y utilización, deben ser claros y asertivos en: la definición de metas y criterios de desempeño (KPI´s) (Muchiri et al., 2013; Kans, 2008; Van Horenbeek and Pintelon, 2014), reportabilidad de calidad (Birolini, 2014; Wei, 2012), sistemas de información consolidados en la organización (Chang et. al, 2014; Hong and Kim, 2002; Park, 2006), bases de datos depuradas y validadas para el análisis (Anaby-Tavor et. al, 2010; Gattiker and Goodhue, 2007) y, finalmente, procesos bien establecidos que garanticen la validez de los resultados (Li et. al, 2007).

La medición y cuantificación del rendimiento es una actividad crítica y evidentemente necesaria para la toma de decisiones y la búsqueda continua de oportunidades de mejora. La productividad y/o efectividad global de los activos/procesos son medidas de rendimiento comúnmente utilizadas en las operaciones, con un alto potencial como impulsores de la mejora continua y la identificación de los focos de pérdida (Anderson and Bellgran, 2015).

En esta línea, un concepto bien conocido para la mejora del rendimiento en producción es el Mantenimiento Productivo Total (TPM) (Nakajima, 1988), herramienta Lean conocida por su enfoque innovador que integra y alinea los objetivos de las áreas de mantenimiento y operación con la estrategia de la organización, con el fin de optimizar la fiabilidad de los activos físicos y garantizar la eficiencia productiva. Además, fomenta la participación y delegación en los trabajadores, por ejemplo, autonomía en las tareas básicas de mantenimiento por parte de los operadores (Ireland, 2001). El objetivo inmediato de TPM es la eliminación total de las pérdidas directas e indirectas en la producción (cero fallos, cero defecto de calidad y cero pérdidas de rendimiento), convergiendo entonces a la efectividad global de los activos, reduciendo los costes y aumentando la productividad. El concepto OEE[2], más que un indicador es una herramienta cuantitativa para medir el rendimiento

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[1] KPI: Key Performance Indicator

[2] OEE: Overall Equipment Effectiveness

global de un sistema productivo. La propuesta presentada por Muchiri (2008) desarrolla el alcance y la relación con el modelo TPM, proponiendo una clasificación de las pérdidas de producción que deriva el cálculo del OEE y sus aplicaciones a diversos procesos productivos. Asimismo, reconoce que el objetivo general del TPM es aumentar la efectividad total (OEE), cuantificada por la disponibilidad de equipos, rendimiento del proceso y la tasa de calidad de la producción. Existen otras propuestas y formulaciones adaptadas a las necesidades y criterios particulares de cada industria, por ejemplo, TEEP (Ivancic, 1998), PEE (Raouf, 1994) y OPE (Muchiri, 2008).

La mayor parte de los avances relacionados con indicadores de rendimiento están fundamentalmente en el campo del diseño conceptual y/o adaptación particular para un proceso productivo. La mayor parte de estos explican y recomiendan los requerimientos básicos para alcanzar indicadores adecuados, por ejemplo: adquisición de datos, procesos de adaptación, necesidades de retroalimentación, objetivos de monitorización, protocolos de validación, entre otros; y por supuesto, la forma en que soportan la toma de decisiones y el respectivo análisis de resultados (Parida and Kumar, 2006; EN15341, 2007). No obstante, la discusión sobre mejorar la representación y reportabilidad gráfica de indicadores sintéticos y efectivos ha sido sutilmente explorada y analizada. Esta característica es considerada de forma subjetiva en algunas propuestas, por ejemplo, en la norma EN 15341: 2007, donde se recomienda que los resultados de KPI deban ser continuamente medidos, de visualización simple y flexible según los cambios de las circunstancias y necesidad de conocimiento, y deban proporcionar retroalimentación rápida a quienes toman decisiones.

Acotando el área de interés y el campo de investigación y aplicación de este trabajo, un problema común en el desarrollo y control de planes de producción y mantenimiento es el logro de los estándares y objetivos planificados por la organización, principalmente debido a la falta de mecanismos prácticos de análisis de información que apoyen la toma de decisiones. En particular, se necesitan herramientas que muestren patrones de deficiencias relacionadas con el uso y el rendimiento del equipo de una manera clara y sencilla. En general, la falta de información y su validez dificultan la realización de pruebas de control que proporcionen alertas tempranas en rendimiento y funcionamiento de los activos. Por lo tanto, el diseño de métodos de análisis cuantitativos y gráficos de fácil interpretación es aún más necesario, ya que facilitan la toma de decisiones mediante la mejora del rendimiento operativo del sistema desde la perspectiva sistémica y particular de cada activo que participa en el proceso.

El concepto de indicadores gráficos, con la perspectiva en reportabilidad, es uno de los instrumentos más valiosos en el área de gestión de proyectos (kersner, 2013). Una gráfica que muestre el resultado real de algunas variables de interés y su evolución en el tiempo, que visualice a priori patrones de comportamiento deseados o no, y que además las compare con su progreso planificado, da la posibilidad de tomar decisiones oportunas ante desviaciones o variaciones indeseadas del proceso productivo. Además, si estas son integradas lógicamente en un reporte consolidado de gestión, con múltiples indicadores de interés que entreguen información fundamental de desempeño de un proceso o negocio, entonces es una herramienta competitiva en beneficio de la productividad, eficiencia y efectividad. De esta forma entonces, el diseño e implementación de estas herramientas debiera ser direccionado desde la gerencia, involucrando estratégicamente todos los niveles de la organización, y facilitando la comunicación, criterios y requerimientos de los futuros usuarios de las herramientas.

En base al contexto antes expuesto, el tema de investigación principal de la presente Tesis Doctoral, presentado en el formato por Compendio de Publicaciones, se desarrolla en la línea del diseño de herramientas de control de gestión, con foco en las áreas de mantenimiento y operaciones, con una fuerte componente teórica y práctica en fiabilidad, mantenibilidad y disponibilidad. Evidentemente, para alcanzar un diseño robusto y con alto potencial de aplicación industrial, la investigación está alineada con las necesidades reales de las empresas específicamente y, dada experiencia laboral/profesional del doctorando, con la industria minera. Para esto, además se incorporan indicadores fundamentales de desempeño, discriminando los principales factores que inciden en el resultado de eficacia del proceso.

Los principales resultados del trabajo de investigación, resumidos en esta Tesis Doctoral, son:

- Tres artículos científicos ISI – JCR publicados.
- Tres artículos en conferencia internacional con sus respectivos proceedings.
- Dos artículos en revisión (segunda revisión específicamente) en revista ISI – JCR.

Es importante mencionar que en cada uno de estos trabajos el candidato a doctor es el primer autor, y el tutor, como segundo autor.

El proyecto de Tesis Doctoral, presentado en el formato por Compendio de Publicaciones, se enmarca dentro de la línea de investigación del grupo Sistemas Inteligentes de Mantenimiento - SIM, perteneciente al Departamento de Organización Industrial y Gestión de Empresas de la Universidad de Sevilla.

2. OBJETIVOS

El proyecto de Tesis Doctoral, presentado en el formato por Compendio de Publicaciones, tiene como objetivo principal de investigación el desarrollo de una propuesta gráfica de control de gestión para las unidades de Mantenimiento y Operaciones, desde la perspectiva individual o agregada como sistema, con el propósito de diagnosticar, analizar y controlar el desempeño de los activos de un proceso productivo. Particularmente, se utilizará como referencia la industria minera para el contexto de análisis, describiendo oportunamente las características y restricciones básicas.

Para cumplir con el objetivo antes señalado, la investigación consideró estratégicamente los siguientes puntos de acción:

1. Revisión y análisis de los modelos de fiabilidad, considerando elementos reparables y no reparables.
2. Investigación teórica y empírica de sistemas de control de gestión que dan soporte a la toma de decisiones en las áreas de Mantenimiento y Operaciones.
3. Investigación de metodologías de análisis que faciliten la búsqueda de oportunidades y toma de decisiones, de forma sistemática y estructurada.
4. Investigación teórica y empírica de indicadores claves de desempeño para las áreas de Mantenimiento y Operaciones.
5. Diseño conceptual de propuestas de herramientas gráficas que den soporte al control de gestión para Mantenimiento y Operaciones.

3. RESUMEN GLOBAL DE LOS RESULTADOS

La presentación resumen de los resultados del trabajo de investigación serán estructurados de acuerdo a la línea cronológica de investigación del candidato, incluyendo resultados como autor principal y coautor respectivamente, tanto para artículos publicados (ISI – JCR y Proceeding internacionales) como para artículos en proceso de revisión. Además, alineado con el objetivo y plan de trabajo mencionado en el punto anterior, cada resultado será debidamente explicado y referenciado según corresponda.

Resultado Nº 1: Investigación y publicación de los modelos de fiabilidad para activos reparables y No reparables.

Descripción y contribución: Modelar, calcular y proyectar la fiabilidad de equipos y sistemas industriales es una tarea básica y fundamental hoy en día para los ingenieros de fiabilidad y mantenimiento, independiente de la naturaleza o genética de estos activos industriales. Esta investigación explica en detalle los modelos estocásticos PRP[3], NHPP[4] y GRP[5], con el desarrollo conceptual, matemático y estocástico según corresponda. Para cada modelo se analiza en detalle la respectiva conceptualización y parametrización.

Aprender detalladamente el paso a paso de cada modelo es una tarea fundamental para aplicar efectiva y correctamente cada modelo. Diversas investigaciones omiten el proceso de resolución y sólo presentan resultados finales indicando el uso del modelo y el uso de alguna herramienta informática con algoritmos integrados. Esto se evidenció en diferentes investigaciones, lo cual motivó a desarrollar una pauta específica conceptual y práctica de resolución para cada modelo paramétrico estocástico antes mencionado. Esto es fundamental para reconocer el valor de este trabajo y su aporte a futuros investigadores que deseen aprender y aplicar estos conocimientos. Es por esta razón, que esta investigación se transforma un procedimiento analítico y explicativo sobre la definición, metodología de cálculo y criterios que deben ser considerados para parametrizar activos industriales bajo cierto nivel de degradación post-mantenimiento, complementando además su análisis con una aplicación numérica que permite evidenciar paso a paso el desarrollo matemático y estocástico según corresponda. La aplicación práctica seleccionada fue desarrollada en la industria minera de Chile.

Esta investigación fue fundamental para fortalecer conceptos básicos de la teoría de fiabilidad, sus modelos y aplicación, y por supuesto, entender en su amplio campo de acción, la gestión de activos físicos.

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[3] PRP: Perfect Renewal Process

[4] NHPP: Non-Homogeneous Poisson Process

[5] GRP: Generalized Renewal Process

Referencia de la (s) publicación (es) como resultado:

- **Viveros P**, Crespo A, Tapia R, Kristjanpoller F, González-Prida V. Reliability stochastic modeling for repairable physical assets. Case study applied to the Chilean mining. DYNA. Volume 91. Pages: 423-431, Julio-Agosto 2016. DOI: 10.6036/7863.
- **Pablo Viveros**, Fredy Kristjanpoller, Adolfo Crespo, René Tapia & Vicente González-Prida. "Mathematical and Stochastic Models for Reliability in Repairable Industrial Physical Assets". Chapter 12. Practices through Energy Engineering and Asset Management. Engineering Science Reference (an imprint of IGI Global). USA, 2015.

Resultado Nº 2: Propuesta gráfica GAMM – Graphical Analysis for Maintenance Management.

Descripción y contribución: Este trabajo de investigación corresponde al primer acercamiento de desarrollo de una herramienta de control de gestión donde, particularmente, se propone una herramienta de soporte lógico para la toma de decisiones en la unidad de mantenimiento. Los datos básicos para el análisis son las intervenciones de mantenimiento (fallos/planificadas) en un horizonte de tiempo acotado por el usuario. Es un método cuantitativo que facilita la identificación de patrones de comportamiento de los activos, por ejemplo el envejecimiento prematuro, dando la posibilidad de tomar decisiones de corto, medio y largo plazo.

Específicamente, esta propuesta tiene como objetivos:

- Visualizar y analizar la fiabilidad de los equipos en una forma gráfica, validando estrategias de mantenimiento.
- Identificar oportunidades de mejoras en gestión de mantenimiento en el corto, medio y largo plazo junto a potenciales inversiones.
- Visualizar de manera simple el número de acciones correctivas entre mantenimientos preventivos, acumulación de fallos en cortos períodos de tiempo, duración de actividades de mantenimiento y secuencias de detenciones de corta duración.
- Identificar oportunamente patrones de comportamiento que correlacionen su desempeño con una incorrecta gestión, por ejemplo: Calidad de las intervenciones.

En esta propuesta se utilizó el estimador no paramétrico Nelson Aalen (Rausand and Hoyland, 2004) de la función de fiabilidad como base para el análisis. Este estimador tiene en cuenta los datos históricos del equipo (total o parcial) y puede proporcionar información valiosa para el analista, incluso con pocos datos disponibles.

La potencialidad de la herramienta se sustenta en dar respuesta (total o parcial) a las siguientes inquietudes de la unidad de mantenimiento:

1. ¿Cuántas intervenciones correctivas (frecuencia) se realizan entre las intervenciones preventivas planificadas?
2. ¿Es correcta la ejecución de las tareas de mantenimiento?
3. ¿Se operan los equipos de manera adecuada?
4. ¿Cuál es la tendencia temporal de las intervenciones?
5. ¿Existe desviación en la frecuencia de ejecución del mantenimiento preventivo?

6. ¿Son coherentes los tiempos de reparación en relación a la carga de trabajo del activo?
7. ¿Es coherente el número de intervenciones con la etapa en que se encuentra dentro de su ciclo de vida?
8. ¿Cómo afectan los tiempos de espera de repuestos en los tiempos de reparación?
9. ¿Es la capacitación del personal de mantenimiento adecuada para implementar la estrategia de mantenimiento en los equipos?
10. ¿Cuál es el impacto de los servicios externos en la confiabilidad y mantenibilidad en los equipos?

A continuación, se presentan en la figura 1 y 2 las principales gráficas utilizadas en esta herramienta.

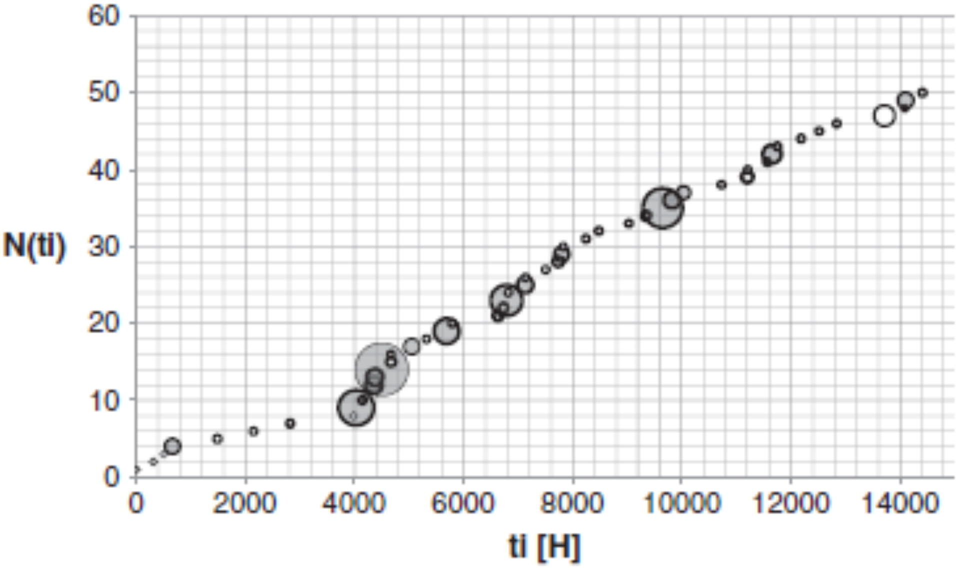


Figura 1 Propuesta GAMM.

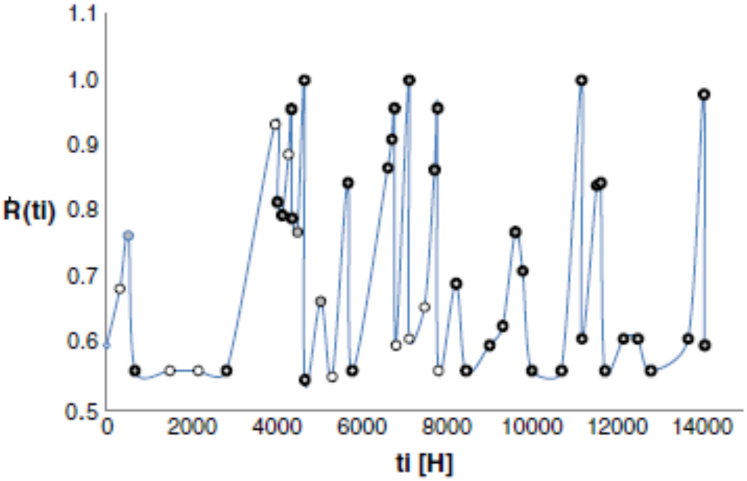


Figura 2 Diagrama de fiabilidad del Activo en el momento de su intervención.

La figura 1, panel principal de GAMM, muestra la gráfica de dispersión de las intervenciones acumuladas de mantenimiento, teniendo como base el número correlativo de intervención (eje y) y la línea de tiempo calendarizada (eje x). Internamente, cada punto de intervención informa sobre: tiempo de reparación (tamaño relativo de las burbuja que bordea el punto de intervención), tipo de intervención (color de burbuja) y estado del equipo al momento de intervenir (color del borde de la burbuja). La figura 2 presenta, en la misma línea de tiempo acumulado calendarizado (eje x), el valor de fiabilidad del activo al momento de ocurrir la intervención de mantenimiento, respetando información adicional como el tipo de intervención y su estado al momento de intervenir.

Los detalles de la herramienta GAMM y sus aplicaciones están descritos en las referencias de la publicación respectiva.

Referencia de la (s) publicación (es):

- Luis Barberá, Adolfo Crespo, **Pablo Viveros**, Raúl Stegmaier. A case study of GAMM (Graphical Analysis for Maintenance Management) in the mining industry. Reliability Engineering & System Safety, Volume 121, January 2014, Pages 113-120.
- Luis Barberá, Adolfo Crespo, **Pablo Viveros**, Adolfo Arata. Proposal of a quantitative graphical analysis to support the decision making in the global maintenance management. “GAMM” method. Quality and Reliability Engineering International – QREI. Volume: 29, Pages: 77 - 87. January 2013.

Resultado Nº 3: Propuesta gráfica GAOM – Graphical Analysis for Operation Management: A Graphical Method to Support Operation Decision Making.

Descripción y contribución: Esta segunda propuesta gráfica soporta decisiones respecto a la operación de plantas industriales, visualizando y analizando parámetros relacionados con la producción, e integrando además características de su mantenimiento. GAOM monitorea las posibles desviaciones del plan de producción, y además incorpora indicadores fundamentales de control de gestión del proceso productivo, tales como: disponibilidad, tiempo fuera de servicio, producción acumulada, entre otros. Por medio de un correcto proceso de filtrado y validez de información base, es posible desarrollar un análisis avanzado por tipo de intervención (fallo, preventiva u operacional). GAOM integra información clave de los eventos de mantenimiento o detención del sistema productivo, con información de producción acumulada durante el periodo de análisis deseado. Adicionalmente se presentan indicadores de gestión que soportan, en conjunto con el análisis gráfico, la toma de decisiones.

Específicamente, esta propuesta tiene como objetivos:

- Visualizar y analizar parámetros asociados a la producción integrando aspectos del mantenimiento, dando la posibilidad de trabajar a nivel del equipo y/o sistema
- Ilustrar gráficamente diferentes aspectos del control de procesos y control de producción.

- Integrar información del mantenimiento con la producción durante un intervalo de tiempo, en beneficio de una perspectiva más amplia para la toma de decisiones.
- Calcular indicadores básicos de rendimiento, y fortalecer los inputs para las decisiones operacionales.
- Entregar salidas gráficas mediante diagramas de dispersión con la integración de indicadores.
- Identificar fenómenos individuales o sistémicos, medir, evaluar o auditar el impacto de decisiones relacionadas con procedimientos operacionales o políticas/estrategias de mantenimiento; Así como la incorporación de la herramienta como una "gran fotografía" que resume el rendimiento global del proceso, en apoyo a la gestión de las unidades de operación y mantenimiento. GAOM resume y complementa el proceso de decisión para reducir las pérdidas de producción y maximizar así los beneficios del negocio.

La potencialidad de la herramienta se sustenta en dar respuesta (total o parcial) a las siguientes inquietudes, diferenciando el aporte según el área.

Área de Operaciones y Producción

1. ¿Cuál es el tiempo operativo entre intervenciones, sean estas planificadas o no planificadas?
2. ¿Cuál es el tiempo No operativo para las intervenciones de clase operacional?
3. ¿Cuál es la tasa de producción de los equipos y del sistema en global?
4. ¿Cuál es la diferencia entre "producción real” y “producción planificada”?
5. ¿Cuál es la diferencia entre "producción real” y “producción nominal”?

Área de Mantenimiento

6. ¿Cuál es la frecuencia de las intervenciones correctivas entre las intervenciones preventivas?
7. ¿Qué tan variables son los "tiempos de reparación” de las intervenciones preventivas y correctivas?
8. ¿Qué tan variables son los "tiempos de operación" post intervenciones preventivas y correctivas?
9. ¿Cuáles son los efectos de la gestión de mantenimiento en los indicadores de desempeño como el tiempo de intervención y el tiempo de operación? ¿Existe correlación?

Integración de las áreas

10. ¿Existe desviación en el rendimiento del equipo? ¿Es posible identificar el área responsable?
11. ¿Existen patrones de desgaste acelerado en el equipo?
12. ¿La capacidad de planta se ajusta a la demanda?

A continuación, se presenta en la figura 3 el panel gráfico base a utilizar en la herramienta GAOM:

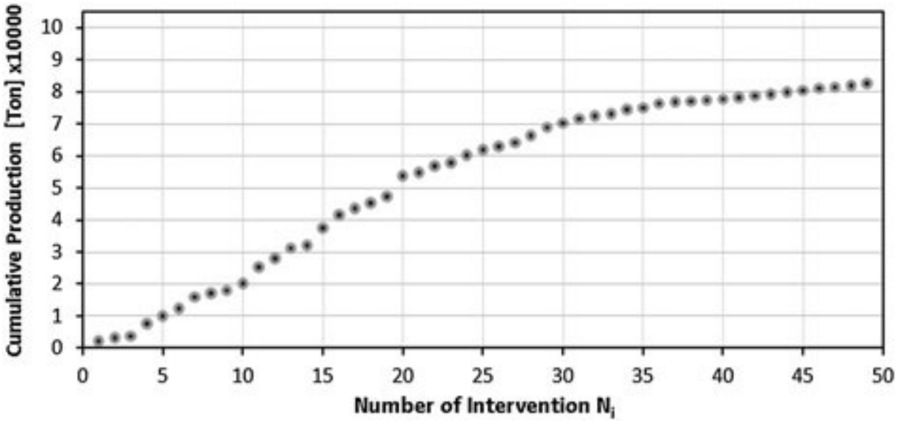


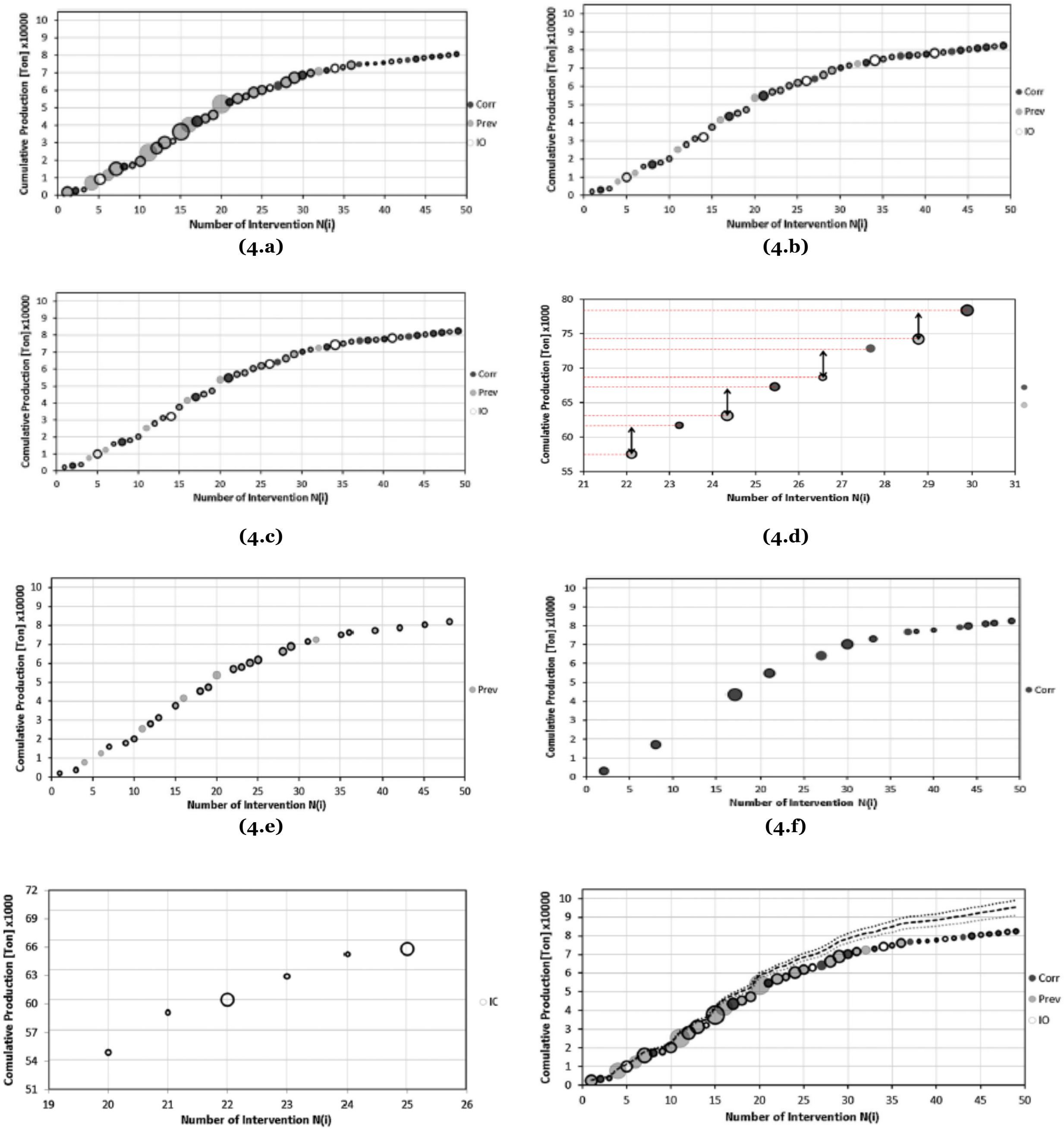
Figura 3 Propuesta GAOM.

La figura 3, panel gráfico base de GAOM, utiliza un diagrama de dispersión de la producción acumulada (eje y) en función del número de intervención (operación y mantenimiento) para la iésima intervención desarrollada a lo largo de un horizonte de tiempo determinado.

A través de esta gráfica base, la herramienta permite desarrollar ocho nuevos análisis (ver figura 4), y por ende 8 nuevas sub gráficas, las cuales se correlacionan con las 2 variables base de la propuesta, número de intervención y producción acumulada. En resumen, estos son: análisis de tiempo entre intervenciones (4.a), análisis de los tiempos fuera de servicio (4.b), análisis de los tiempos entre intervención filtrando los eventos correctivos (4.c), análisis de los tiempos fuera de servicio filtrando los eventos preventivos (4.d); análisis de la política de mantenimiento preventivo establecida (4.e), análisis de los tiempos fuera de servicio filtrando las detenciones operacionales (4.f), análisis de los tiempos operativos y la producción meta (4.g) y el análisis de desviación entre la producción acumulada real y la planificada como meta (4.h).

El procedimiento de aplicación para el análisis GAOM depende del nivel de conocimientos y del interés particular de los analistas. El punto de partida para solicitar información podría ser:

1. Interés de identificar algunos fenómenos particulares (por ejemplo: sobrecarga, desgaste acelerado, etc.) utilizando los gráficos propuestos para explicar y medir su efecto, dando soporte y validez a los resultados de los KPI’s.
2. Búsqueda general de fenómenos que tengan efecto sobre el incumplimiento de objetivos (baja productividad, baja disponibilidad y/o utilización, etc.), con lo cual, el análisis GAOM apoya de forma preliminar a identificar la causa de la improductividad.



(4.a) (4.b)

(4.c) (4.d)

(4.e) (4.f)

(4.g) (4.h)

Figura 4 Propuesta GAOM.

La lectura y análisis de estos gráficos se recomienda que sea desde la perspectiva general (4.a, 4.b y 4.g) a lo particular (4.c, 4.d, 4.f, 4.h, 4.i).

Los detalles de la herramienta GAOM y sus aplicaciones están descritos en las referencias de la publicación respectiva.

Referencia de la (s) publicación (es):

Viveros Gunckel, P., Crespo Márquez, A., Barberá Martinez, L., and Gonzalez Rossel, J. P. (2016) Graphical Analysis for Operation Management: A Graphical Method to Support Operation Decision Making. Qual. Reliab. Engng. Int., 32: 2299–2311. DOI: 10.1002/qre.1936

P. Viveros, A. Crespo, L. Barberá, F. Kristjanpoller, R. Stegmaier, E. Johns, T. Grubessich. General Framework about Graphical Analysis for Operation Management. The Annual European Safety and Reliability Conference (ESREL). Zurich, Switzerland. Sept 7-10, 2015. DOI: 10.1201/b19094-140.

Resultado Nº 4: Propuesta gráfica GAOEM – Graphical Analysis for Overall Effectiveness Management: A Graphical Method to Support Operation and Maintenance Performance Assessment.

Descripción y contribución: Esta tercera propuesta gráfica facilita la toma de decisiones en relación a la búsqueda de la efectividad total (OEE[6]), principalmente condicionada al desempeño de la operación y el mantenimiento en la industria minera. El marco propuesto "Análisis Gráfico para la Gestión de la Efectividad Global" (GAOEM) se utiliza en un proceso industrial real, integrando los principales indicadores de desempeño para mantenimiento y operaciones, realizando además una contextualización al indicador de efectividad global OEE/OAE[7]. GAOEM facilita el control y el análisis mediante el uso de indicadores específicos (panel gráfico propuesto), lo cual simplifica la lectura e interpretación eficiente de los datos, acelera el análisis y búsqueda de fenómenos de interés, direcciona la búsqueda de oportunidades de mejora; es decir se transforma en un soporte potente para la toma de decisiones. El método GAOEM está inspirado en el GAMM y GAOM, presentados previamente.

Específicamente, esta propuesta tiene como objetivos:

- Controlar y diagnosticar la efectividad global del equipo de producción.
- Acortar los tiempos de diagnóstico e interpretación de los datos históricos.
- Sistematizar el proceso de identificación de potenciales problemas relacionados con el uso de los activos y aumentando así la productividad y la rentabilidad.
- En cuanto a la aplicabilidad, además de la industria minera, GAOEM puede ser adaptada a otros procesos de producción con intereses similares en control y análisis, como es el caso de la industria petroquímica, celulosa, cervecera, entre otros.

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[6] OEE: Overall Equipment Effectiveness

[7] OAE: Overall Asset Effectiveness

- GAOEM permite el desarrollo sistematizado y normalizado de dos tareas fundamentales de las unidades productivas: el control y el análisis.

La potencialidad de la herramienta se sustenta en dar respuesta (total o parcial) a las siguientes inquietudes.

1. ¿Se están cumpliendo los objetivos de producción para el período de análisis?
2. ¿Cuál es el resultado, en un nivel de rendimiento global, de las áreas Operación y Mantenimiento?
3. ¿Cuál es la responsabilidad de cada área en la eficiencia global del proceso?
4. ¿Cuál es la tendencia de los resultados de las áreas?
5. ¿Qué fenómenos, entendiéndolos como hipótesis de causas primarias de desviación en el rendimiento, son evidentes en los resultados?

GAOEM se construye a partir de 5 indicadores claves:

- Disponibilidad [A] Porcentaje de tiempo total en el que un activo puede cumplir la función para la que fue diseñada. La disponibilidad no significa necesariamente que el equipo está funcionando, pero si el tiempo en el que se encuentra apto para trabajar.
- Utilización [U] Porcentaje de tiempo total en que el activo se utiliza para fines productivos, independientemente de la tasa de producción.
- Utilización Efectiva [U_e] Porcentaje del tiempo disponible en que el activo está siendo utilizado para fines productivos, sin tener en cuenta la tasa de producción.
- Rendimiento [P] Este índice incorpora las pérdidas de eficiencia debido a las detenciones menores (parcial / total), donde la producción se interrumpe debido a una máquina que funciona con capacidad ociosa o por un requisito operativo (carga o tasa de producción) inferior o superior a la establecido por el diseño en el proceso.
- Calidad [Q] Este índice incorpora las pérdidas de eficiencia que se derivan de las desviaciones en los estándares de calidad establecidos y/o retrabajos de material.

OEE (Nakajima, 1988), Efectividad Global de los Equipos, plantea 6 agentes de pérdidas y los organiza e integra en tres enfoques de eficiencia: Mantenimiento, Producción y Calidad. Esta definición de OEE se muestra en la figura propuesta por Seiichi Nakajima en su libro Introducción al TPM: Mantenimiento Productivo Total.

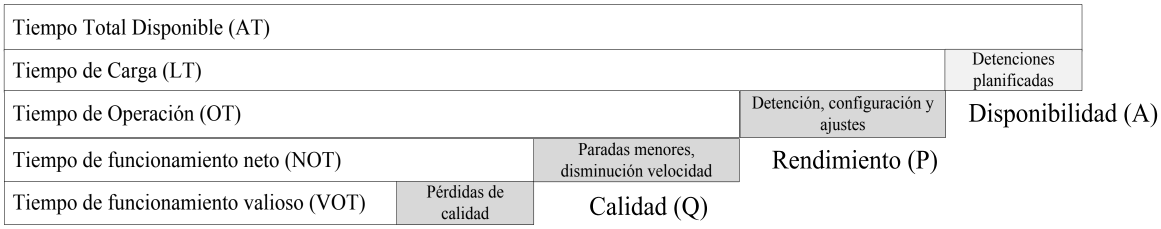

Figura 5 Definición y Cálculo de OEE

Donde se calcula como OEE=A*P*Q.

GAOEM propone una adaptación a esta herramienta para el caso de la Industria Minera en base a indicadores previos.

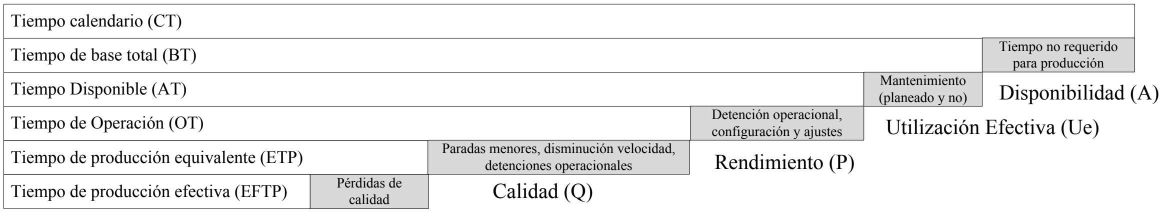

Figura 6 Adaptación definición y cálculo OEE para industria minera

Donde se calcula como $OEE=A*U_e*P*Q$. Los tiempos indicados en la gráfica 6 se detallan a continuación:

- Tiempo calendario (CT) Horizonte de tiempo máximo según los turnos de producción. Ejemplo: 24 horas todos los días, con un total de 365 días al año. CT: 8.760 hora.
- Tiempo de base total (BT) Horizonte de tiempo declarado para producir. Ejemplo: dos turnos de 12 horas por día, con un total de 320 días al año. BT: 7.680 horas.
- Tiempo disponible (AT) Horizonte de tiempo disponible, se le excluyen las intervenciones planeadas o correctivas. Ejemplo: La cantidad de tiempo en mantenimiento correctivo y preventivo se registró a 550 horas. AT: 7.680 - 550 = 7.130 horas.
- Tiempo de operación (OT) Horizonte de tiempo de operación. Se le descuentan las intervenciones operacionales no planificadas y planificadas que afecten la producción total. Ejemplo: La cantidad de tiempo en la detención operativo se registró a 120 horas. Con esto, OT: 7.130 - 120 = 7.010 horas.
- Tiempo de producción equivalente (ETP) Este punto busca incorporar las desviaciones con respecto a la carga de la producción real y la velocidad relativa de la capacidad productiva del diseño. El objetivo es calcular un tiempo de funcionamiento equivalente como si el equipo hubiese operado en su capacidad programada (ideal) del diseño. Ejemplo: A partir de las 7.010 horas producidos (OT), se encuentra que el 25% de las veces el equipo funciona a 80 % de la capacidad nominal programada. La aproximación numérica es:
- ETP= (OT)·(75%·100%+25%·80%)/(100%)= (OT)·95%=6.659,5 horas
- Tiempo de producción efectiva (EFTP) Incorpora las pérdidas de producción causadas por un incumplimiento de las normas de calidad, es decir, el porcentaje de la producción en la que lo que se produce en un período finito no cumple con el estándar establecido del proceso. Ejemplo: A partir de los 6.659,5 horas equivalentes producidos, se registró que el 8% de la producción es rechazado por el control de calidad, a continuación: EFT= ETP·(100%-8%)/(100%)=92%·6.659,5=6.126,7 horas.

El método GAOEM entrega la información de manera gráfica facilitando y simplificando su análisis, siguiendo la evaluación de indicadores (individual y acumulado) a medida que se presenten las intervenciones. Para esto es primordial comprender su base conceptual y numérica estudiada con anterioridad.

A continuación, se presenta en la figura 5, 6 y 7 del panel gráfico base a utilizar en la herramienta GAOEM:

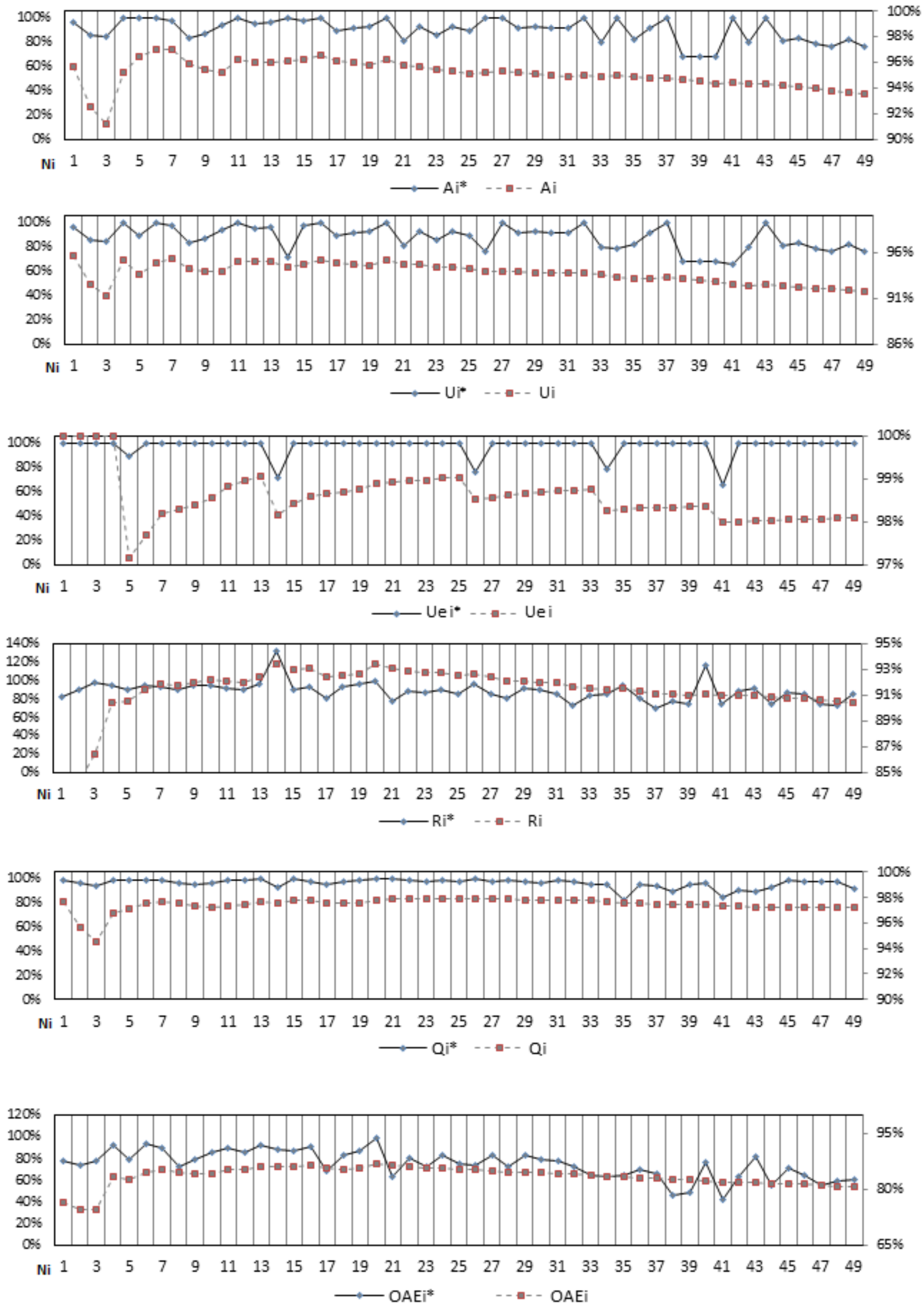

Figura 7 Propuesta GAOEM – Panel de control de KPI de Rendimiento Global.

incorporando indicadores fundamentales de fiabilidad y rendimiento.

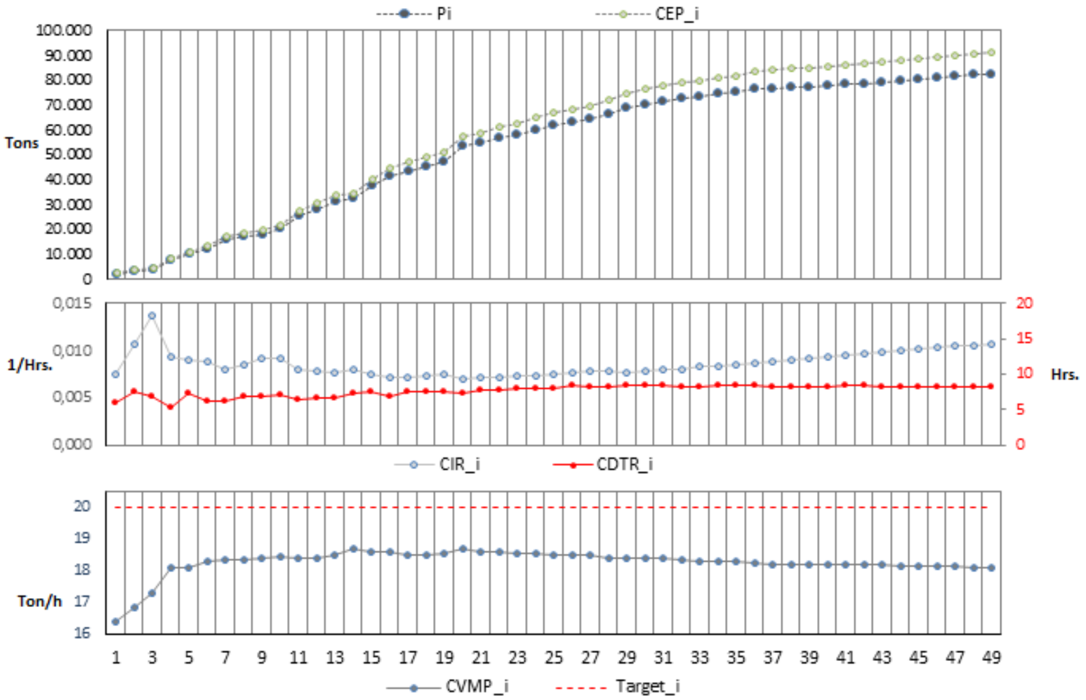

Figura 8 Propuesta GAOEM - Panel de Control para el análisis de las brechas de producción y sus principales causas

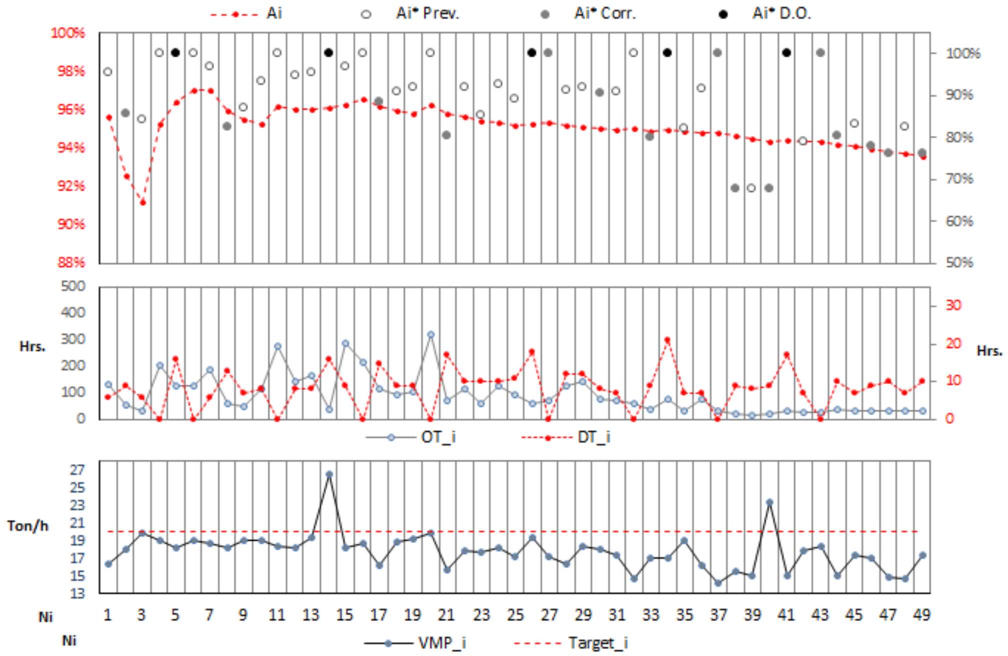

Figura 9 Propuesta GAOEM - Panel de Control para el análisis de tendencia y sus principales causas

Los detalles de la herramienta GAOEM están descritos en las referencias de la publicación respectiva. Cada panel gráfico está desarrollado con sus respectivas reglas de lectura, potencialidades de identificación de fenómenos y reglas de interpretación.

Referencia de la (s) publicación (es):

P. Viveros, A. Crespo, L. Barberá, F. Kristjanpoller, R. Stegmaier, E. Johns, T. Grubessich. General Framework about Graphical Analysis for Overall Effectiveness Management. The Annual European Safety and Reliability Conference (ESREL). Glasgow, Scotland. Sept 25-29, 2016. CRC Press, 2016ISBN: 149878898X, 9781498788984

Artículo en revisión en el Journal ISI – JCR: Qual. Reliab. Engng. Int. 2017.

Resultado Nº 5: Marco de referencia para seleccionar técnicas de análisis de criticidad en ambientes industriales.

Descripción y contribución: Esta cuarta herramienta/metodología aborda, desde un punto de vista analítico, el desempeño de los procesos productivos y políticas de mantenimiento en el entorno industrial, concretamente los mecanismos de jerarquización de activos dentro de un sistema que permitan discretizar aquellos equipos considerados como críticos, es decir, aquellos que en caso de fallo tendrían un alto impacto en producción, en costes, en seguridad humana o/y en seguridad ambiental, y que por tanto se les debe asignar una mayor cantidad de recursos. Resulta necesario en cualquier entorno industrial, identificar aquellos procesos, áreas, equipos o componentes que generan un mayor impacto por ocurrencia de un fallo, es decir aquellos potencialmente críticos. El impacto es el grado en que la ocurrencia de un fallo en un elemento puede afectar a la continuidad del proceso o negocio, y es tratado en la literatura desde diferentes enfoques: frecuencia de fallo, impacto sobre producción, impacto sobre la seguridad de las personas, impacto sobre el medio ambiente, función del activo total o parcialmente interrumpida, entre otros.

Específicamente, el objetivo de esta propuesta es identificar la técnica/método de jerarquización de activos que mejor se ajusta a un contexto de operación concreto en base a un conjunto de criterios y variables que permitan, además, establecer cómo debe aplicarse la técnica de jerarquización (niveles de información necesarios, entre otros). El objetivo es determinar del grado de criticidad de los equipos/modos de fallo en una planta industrial, identificando los agentes críticos sobre los cuales se deben destinar los recursos para minimizar la ocurrencia de fallos, atenuar sus efectos, eliminar o controlar los modos de fallo, renovar determinados equipos o generar nuevas políticas de mantenimiento, minimizando los costes globales y mejorando la gestión los activos.

La metodología propuesta (Figura 10) se ha construido a partir de preguntas simples que hacen referencia a características del contexto operacional existente, la disponibilidad de información, así como las competencias y formación de los trabajadores. La metodología presenta principalmente dos conjuntos de preguntas. El primero de ellos está constituido por preguntas orientadas al diagnóstico del escenario existente. El segundo conjunto, incorpora un árbol de decisión sobre las distintas técnicas potencialmente aplicables en función de los requerimientos. Posteriormente se cruzan ambos conjuntos de información, identificándose una técnica concreta en caso de existir concordancia entre los dos conjuntos o estableciendo sugerencias de mejoras o selección de otra técnica de jerarquización en caso de existir discordancia.

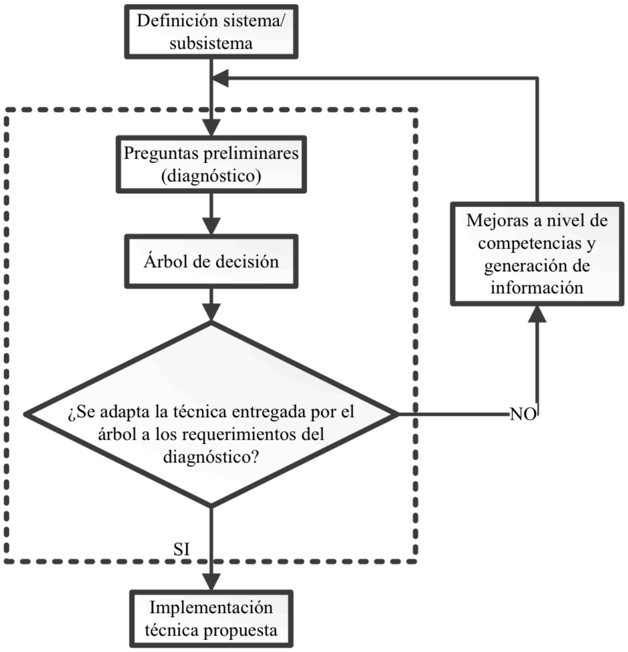

Figura 10 Diagrama del Proceso metodológico.

Una vez realizada la evaluación para cada una de las técnicas, el diseño de la metodología propuesta se fundamenta principalmente en el contexto operacional concreto existente en la empresa. En base a éste, la metodología es capaz de sugerir la técnica de jerarquización que mejor se adapta a las circunstancias y la forma en que ésta debe ser utilizada, permitiendo discretizar aquellos activos críticos de manera inequívoca. Para facilitar la aplicación de la misma, la metodología propuesta se ha representado mediante un árbol de decisión (Figura 11).

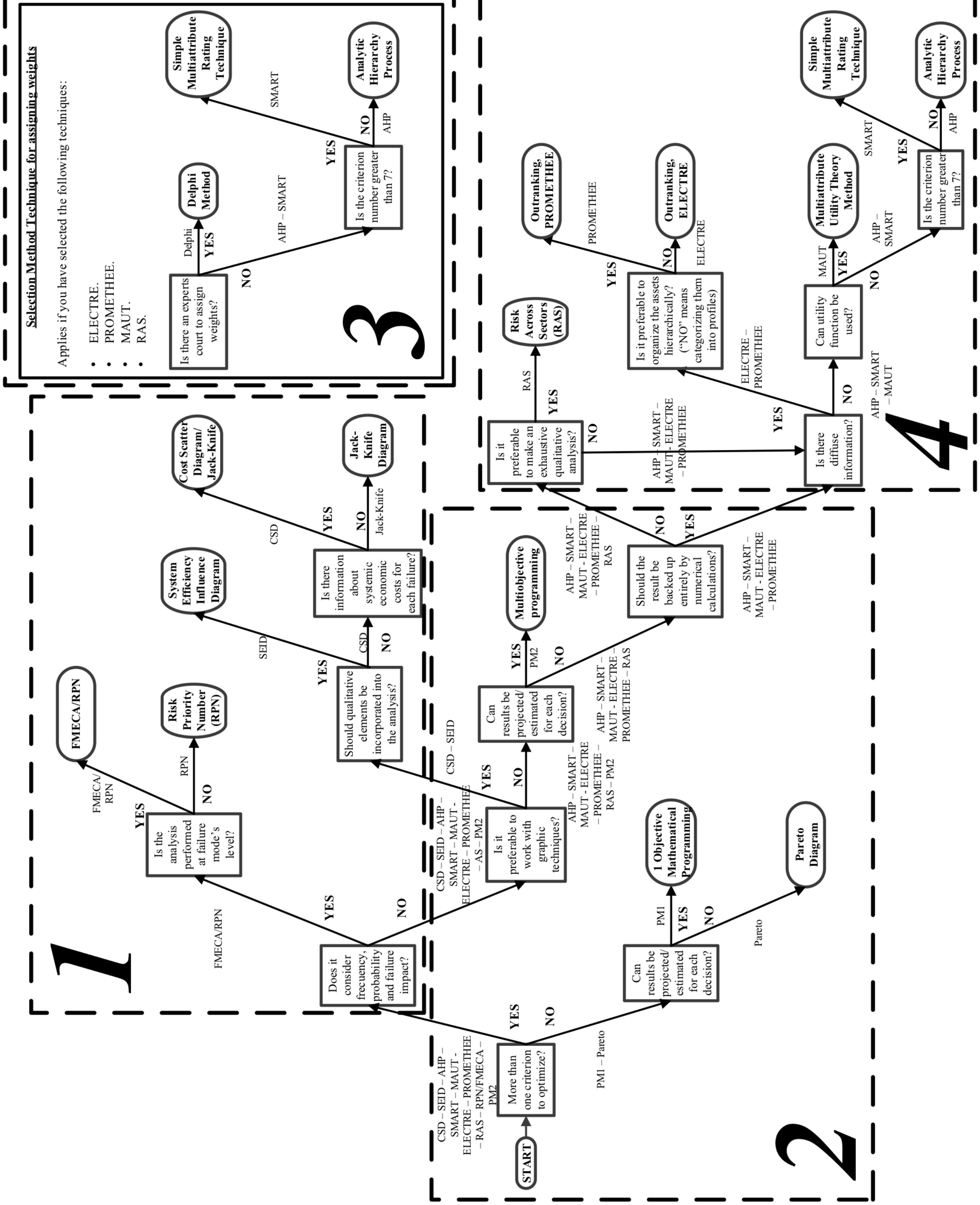

Figura 11 Árbol de decisión.

La primera parte de la metodología consiste en un conjunto de preguntas básicas que permiten acotar de forma preliminar el espectro de técnicas de jerarquización de activos que puede resultar de aplicación para el contexto operacional concreto, en base a tres perspectivas: registros en base de datos, gestión de la información y competencias del personal. Ver siguiente tabla 1 para el detalle de estas.

Tabla 1: Conjunto de preguntas preliminares.

I. REGISTROS DE BASE DE DATOS	***1***	***2***	***3***	***4***
1. La empresa dispone de un sistema computarizado de gestión de mantenimiento ERP.				
2. Cada componente está identificado, codificado y asociado a un sistema dentro de toda la planta.				
3. Se dispone de un sistema de registros de datos históricos a nivel de ubicación técnica para cada evento.				
4. Las configuraciones lógicas de la planta están todas registradas.				
5. Los elementos registrado en el sistema se pueden discriminar por disciplina (mecánica, eléctrica, instrumental, estructural, etc.).				
II. GESTIÓN DE LA INFORMACIÓN	**1**	**2**	**3**	**4**
Información Cuantitativa				
1. Tiempos de operación y detención de equipos				
2. Costes de fallo, a nivel particular y agregado				
3. Cantidad de eventos en mantenimiento (intervenciones, accidentes, etc.)				
Información Cualitativa				
4. Sistemas de reserva (buffers, tipos de intervenciones a cada equipo, redundancias)				
5. Medidas generales de mitigación de efectos de fallo.				
6. Características intrínsecas del fallo (frecuencia, severidad, características de su detección)				
7. Impactos del fallo (ambientales, producción, seguridad y salud ocupacional)				
KPI				
8. Asociados a disponibilidad y eficiencia				
9. Asociados a costes				
III. COMPETENCIAS DEL PERSONAL	**1**	**2**	**3**	**4**
1. El personal está calificado para el ingreso/carga de datos al sistema de mantenimiento ERP				
2. Cálculo de porcentajes en variables cuantitativas.				
3. Manejo de Excel básico (funciones, gráficos, etc.).				
4. Simulación de escenarios en función de variables cualitativas.				
5. Conocimientos matemáticos medios (álgebra de matrices, gráficos en 3 dimensiones, curvas de nivel).				
6. Diseño de funciones en base a información histórica.				
7. Estimación de niveles de aceptación y rechazo en variables del modelo.				
8. Proyección de datos.				
9. Generación de información en conjunto con el personal de la planta.				
10. Conocimientos medios en investigación operativa (programación matemática).				
11. Simulación de escenarios para cada decisión posible de tomar en el modelo.				

IV. ÁRBOL DE DECISIÓN (Requerimientos Internos)	**SI**	**NO**
1. ¿Se desea optimizar más de una función objetivo o criterio?		
2. ¿El problema puede ser abordado desde perspectiva de frecuencia, probabilidad de detección e impacto de fallo? (a nivel cuantitativo o cualitativo).		
4. ¿El análisis puede ser realizado a nivel de modo de fallo?		
5. ¿Se quiere trabajar con técnicas de tipo gráfico?		

7. ¿Se deben incorporar elementos/variables de tipo cualitativo al análisis? (variable no numéricas, comparaciones por puntajes, políticas, sistemas de reserva, etc.)		
8. ¿Se pueden proyectar/suponer resultados/consecuencias para cada decisión a tomar?		
9. ¿Existe información de los costes económicos sistémicos asociados al posible fallo de cada equipo/sistema?		
11. ¿El resultado debe estar respaldado en su totalidad por cálculos numéricos?		
12. ¿Se desea realizar un análisis cualitativo exhaustivo? (juicio de expertos, observaciones especiales, aspectos éticos/políticos/organizacionales, etc.)		
13. ¿Existe información difusa? (incertidumbre, variabilidad, falta de información o criterio)		
14. ¿Se desea jerarquizar activos o categorizarlos en perfiles determinados?		
15. ¿Se puede utilizar una función global que represente utilidad total (en una unidad común) y funciones para cuantificar el aporte de cada criterio a ésta?		
16. ¿El número de criterios es mayor a 7?		
17. ¿Se puede generar o se dispone de tribunal de expertos capaz de asignar ponderaciones numéricas para cada criterio?		

Las tres primeras secciones hacen referencia al contexto operacional de la empresa, mientras que la cuarta sección considera los requerimientos necesarios por parte de la empresa con respecto al conjunto de posibles técnicas a implementar. Se utiliza la siguiente escala de respuestas:

- Nunca: El aspecto no se presenta nunca, no existe información ni competencias.
- Casi nunca - Malo: El aspecto se presenta pocas veces, muy poca información.
- Generalmente – Bueno: Se aprecian resultados aceptables, el aspecto se trabaja poco.
- Siempre – Excelente: Existe amplia información y competencias al respecto.

La segunda parte de la metodología utiliza un árbol de decisión el cual indica las acciones a realizar en función de una o varias variables (Figura 11).
Los detalles de la herramienta/metodología propuesta están descritos en la referencia del trabajo respectivo. Además, es complementado con un caso de aplicación detallado.

Referencia de la (s) publicación (es):

P. Viveros, A. Crespo, L. Barberá, Vicente Gonzalez-Prida. Marco de referencia para seleccionar técnicas de análisis de criticidad en ambientes industriales. Under revision since December, 2016. DYNA.

Observación: Aunque se presentaron cinco productos como resultados del trabajo de investigación, a efectos formales del proyecto de Tesis Doctoral, presentado en el formato por Compendio de Publicaciones, se considerarán como resultados principales los dos artículos ISI – JCR y el capítulo de libro presentados en el capítulo 7 de este documento de Tesis, cumpliendo entonces con los requisitos de ser el primer autor en cada uno de estos, más la participación del tutor como segundo autor.

4. DISCUSIÓN

El escenario actual de competitividad en la industria exige una mayor integración de la gestión de mantenimiento con la gestión de la producción, con el objetivo final de producir a un coste mínimo en todo el ciclo de vida del negocio, y satisfaciendo evidentemente los estándares y niveles de servicio de los clientes. Para alcanzar este objetivo, el diseño de indicadores clave de desempeño (KPI) ha demostrado ser una estrategia efectiva en esa ruta, entendiéndose que satisfacen los requerimientos de información de quienes gestionan los procesos productivos, están correctamente conceptualizados y diseñados, y son integrados en reportes gráficos de simple lectura, interpretación y con alto valor añadido en términos de la información que facilita el diagnóstico, control y toma de decisiones.

Un problema transversal en el desarrollo y control de planes de producción y mantenimiento es el logro de los estándares y objetivos planificados por la organización, principalmente debido a la falta de mecanismos prácticos de análisis de información que apoyen la toma de decisiones. En particular, se necesitan herramientas que muestren patrones de deficiencias relacionadas con el uso y el rendimiento del equipo de una manera clara, sencilla y oportuna.

En general, la falta de información y su calidad dificultan la realización de pruebas de control que proporcionan alertas tempranas en rendimiento y funcionamiento del equipo. Por lo tanto, el diseño de métodos de análisis cuantitativos y gráficos que son fáciles de interpretar es aún más necesario.

Disponer de una visión global y particular del rendimiento de los activos y el sistema productivo, de forma oportuna y muchas veces proactiva (identificación temprana de fenómenos), soporta concretamente el control de gestión de la operación, entendiendo además que la gestión del mantenimiento es un pilar fundamental para la identificación de factores de pérdidas de valor y, por ende, cumple una función estratégica para la maximización de los beneficios del negocio.

El trabajo de investigación integra un panel gráfico para cada herramienta desarrollada, incorporando múltiple información de interés y definiendo detalladamente las reglas de construcción, análisis e interpretación. Estas herramientas son fundamentales en la propuesta metodológica, ya que son el canal de comunicación directo con los usuarios y analistas que identifican las fuentes de pérdidas de eficacia de la operación. Por esta razón, es necesario entregar información de forma clara y sencilla, dando las directrices para la asignación futura de recursos técnicos y económicos que aseguren el cumplimiento de las metas definidas.

A continuación, se presenta la discusión respecto a 4 inquietudes (cuestiones sobre los equipos de control de gestión en Mantenimiento y Operaciones) que fueron identificadas al momento de aplicar las propuestas de reportabilidad y análisis. El objetivo de este punto es discutir al respecto y recomendar guías para asegurar la implementación y exitoso uso de las herramientas.

Inquietud Nº 1: Si no se dispone de una base de datos consolidada, ¿conviene aplicar estas herramientas?

Para alcanzar eficaz y eficientemente los objetivos de las herramientas de control, es recomendable elaborar, en una etapa temprana de implementación, un sistema de información de alto rendimiento (Li et. al, 2007; Bunea et. al, 2008, March and Hevner, 2007) que permita hacer las consultas y análisis preestablecidos. La figura 12 presenta de forma simple la relación entre las posibles fuentes de datos, su procesamiento y el resultado de un sistema de información consolidado que responda a los requerimientos. Evidentemente este proceso debe ser supervisado y soportado por la experiencia y conocimiento de la organización y el equipo de trabajo responsable.

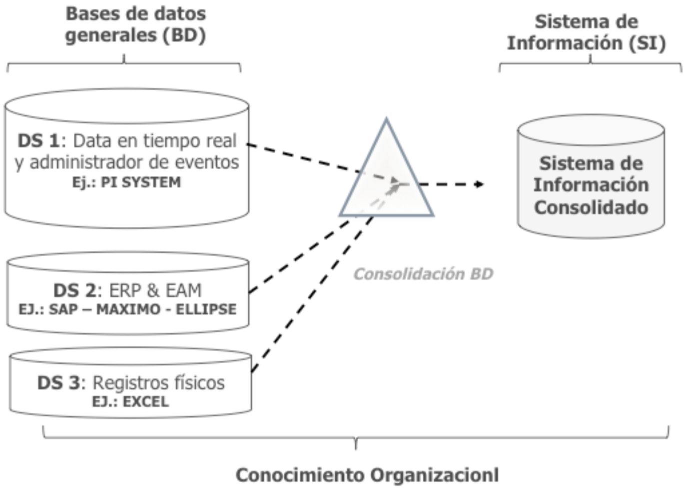

Figura 12 Unificación de la Base de Datos

Del punto de vista práctico, existe la posibilidad que los requerimientos no sean 100% resueltos por el actual sistema de información de la organización, lo cual obligaría la creación de un sistema complementario y/o modificación del actual sistema. En tal caso, es fundamental el trabajo colaborativo donde participen personas con amplios conocimientos de los sistemas de información actuales ya que, de no tener una visión global, podrían existir fuentes de información precisas para los requerimientos, pero que no sean consideradas por desconocimiento.

Es esta misma línea, actualmente un Cyber-Physical Systems (CPS) se define como una tecnología transformadora para la gestión de sistemas interconectados entre activos físicos y sus capacidades computacionales (Baheti, 2011), capaz de integrar la producción, logística y servicios en las prácticas industriales actuales, transformando entonces la industrias de hoy en la Industria 4.0 con un alto potencial económico (Lee et. al, 2015). Uno de los principales requerimientos para aplicar CPS es la conectividad avanzada, que asegura la adquisición de datos en tiempo real de los activos (mundo físico) y la retroalimentación de información desde el repositorio (ciberespacio), donde deben existir capacidades analíticas y computacionales. La información capturada se puede analizar en términos de equipo o sistema global, y dependerá de la posición física de los sensores que controlan la salida de producción (conexión inteligente). En el mantenimiento, los sistemas de captura automática suelen proporcionar datos sobre parámetros operacionales (enfoque en el pronóstico y la aplicación de gestión de la salud), datos relacionados con el estado del activo (encendido / apagado) y tiempos de inactividad. De hecho, el repositorio de datos también debe complementarse con sistemas de gestión de notificaciones de mantenimiento y órdenes de trabajo (Birollini, 2014; Gattiker and Goodhue, 2007). Para ello, una solución ERP permite la integración completa del flujo de información de todas las áreas funcionales mediante una única base de datos y accesible a través de una Interfaz unificada (López and Salmerón, 2014). Como consecuencia de la globalización y de la competitividad constante en el mercado, las empresas más importantes, como por ejemplo la industria Minera, han adoptado paquetes de ERP para integrar plenamente, estandarizar y coordinar sus procesos de negocio.

Inquietud Nº 2: ¿Qué procesos deben estar resueltos y consolidados en la organización para implementar exitosamente las herramientas?

Se recomienda que las organizaciones que deseen implementar reportes avanzados de control y gestión en Mantenimiento y Operaciones, dispongan al menos los siguientes puntos:

- Procesos consolidados de captura de datos y herramientas de soporte implementadas y aprendidas por los usuarios.
- Conciliación de la base de datos que será utilizada para el desarrollo de los reportes. Esto implica reuniones de trabajo con participantes de Mantenimiento y Operaciones.
- Conocimiento acabado de los actuales reportes, indicadores, métricas y criterios de cálculo.
- Árbol de desagregación de equipos (jerarquías en los sistemas productivos), y catálogo de fallos existente.
- Conocimiento de las herramientas de confiabilidad en uso y su nivel de implementación y aprendizaje.

Para conocer esta información en detalle, se recomienda desarrollar a priori una breve auditoría a la obtención de información.

Inquietud Nº 3: ¿Es posible integrar las herramientas propuestas con otros métodos o mecanismos de análisis?

Idealmente, la integración de nuevas herramientas de control debiera ser adaptada al contexto de trabajo y cultura organizacional. Por lo general, el proceso de puesta en marcha debiera ser en paralelo a los actuales mecanismos de control y análisis y, en la medida que los procesos de uso y aprendizaje hayan sido resueltos y consolidados, debiera entonces eliminarse el sistema o las herramientas antiguas. Las propuestas desarrolladas tienen un alto potencial de integración con herramientas como: SW[8] de análisis RAM[9], métodos de criticidad y jerarquización, análisis de priorización, entre otros. Para lograr la efectiva integración, evidentemente deben diseñarse secuencias lógicas de análisis, protocolos de comunicación entre los actores claves de los procesos, estandarización de criterios de análisis e interpretación y regla básicas de lectura para la secuencia de análisis.

A modo de ejemplo, se anexa un reporte de fiabilidad diseñado para una empresa minera de Chile, el cual integra: Software RelPro de fiabilidad, priorización (Jack Knife y Pareto) y GAMM. Para más detalle ver Anexo 1 al final del documento.

Inquietud Nº 4: Describa ventajas, desventajas y potencialidades de la línea de investigación, específicamente de herramientas de control y análisis avanzando para Mantenimiento y Operaciones.

Como ya ha sido descrito anteriormente, esta propuesta metodológica está diseñada para acelerar los procesos de análisis de desempeño de los activos físicos en cualquier escenario o realidad industrial.

En términos de ventajas se tiene:

- Sistematización del proceso de captura de datos, asegurando la correcta catalogación de los distintos tipos de eventos de detención en el proceso productivo (calidad del dato) y el almacenamiento total de los eventos que interrumpen la continuidad operacional (cantidad de datos).
- Discriminación de eventos de alto impacto, a partir de la ponderación por consecuencia que se obtiene de la representación de cada una de las configuraciones lógico funcionales de los equipos, en el modelo de seguridad de funcionamiento del proceso productivo.

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[8] SW: Software

[9] RAM: Reliability, Availability and Maintainability.

- Reconocimiento de la afectación provocada por los distintos eventos en los indicadores individuales y sistémicos de disponibilidad y utilización del proceso productivo, a partir de la catalogación efectiva de cada uno de los eventos de detención y la trazabilidad otorgada por el árbol de dependencias funcionales de los equipos dentro del flujo de proceso.
- Evaluación de la criticidad de los equipos, a partir de la consulta de reportes con distinto foco de análisis y periodicidad, distinguiendo reportes ejecutivos y reportes especializados con frecuencia semanal, mensual y anual.
- Identificación de oportunidades de mejora y seguimiento de la efectividad del proceso de implementación de los planes de acción concretos, a partir de herramientas de control y evaluación.

En términos de desventajas se tiene:

- Dependencia de sistemas informáticos de captura automática de datos en campo, que requieren de un proceso de parametrización y conocimiento acabado para asegurar una base de datos homogénea y representativa de la realidad industrial.
- Requerimiento de un proceso robusto de conciliación de datos, dependiente de trabajadores con responsabilidad técnica en el proceso productivo (mantenedores y operadores), con frecuencia diaria y sin capacidad de automatización total (dada la naturaleza de la discriminación de eventos).
- Requerimiento de una función de análisis periódica en las procesos productivos, que la mayoría de las veces se encuentra subordinada a meros aspectos administrativos y no a la evaluación y seguimiento de oportunidades de mejora.
- Necesidad de consensuar criterios corporativos para la interpretación correcta de la información que emana de los distintos reportes de ingeniería de fiabilidad, de manera que cada función de acuerdo a su particular foco saque provecho en la toma de decisiones.

En términos del potencial de este tipo de herramientas, como resultado esperado se tiene:

- Herramientas capaces de generar bases de información de rápida consulta y masificación, para que cada trabajador de una organización de acuerdo a su rol y a sus necesidades particulares, posea el conocimiento suficiente para una toma de decisiones ágil y rigurosa.
- Herramientas que se convierten en la carta de navegación de los procesos productivos, de acuerdo a la periodicidad establecida y el nivel de especialización de los distintos reportes. Esto es, a partir de herramientas simples y de fácil

interpretación identificar oportunidades de mejora orientadas preferentemente hacia aquellos equipos que mayor impacto generan en el proceso productivo.

- Herramientas capaces de conectar la función de análisis con las funciones más ejecutoras en el proceso productivo. Esto es, cerrar el proceso de la mejora continua que comienza con la identificación de una oportunidad y culmina con la evaluación de la efectividad de los cambios implementados, ya sea a partir de un nuevo procedimiento o el cambio en alguna práctica habitual de una actividad de mantenimiento o de operaciones.

5. CONCLUSIONES

De acuerdo al objetivo principal propuesto en el proyecto de Tesis Doctoral, presentado en el formato por Compendio de Publicaciones, se han expuesto resumidamente cinco resultados específicos, los cuales se alinean a la problemática de control de gestión para Mantenimiento y Operaciones, dando soporte efectivo a tareas de diagnóstico, análisis y control de desempeño de los activos. Para alcanzar este resultado, la investigación debió desarrollarse tanto desde la perspectiva teórica como práctica, ya que la aplicación y validación de cada propuesta era parte de los resultados esperados.

Respecto al primer resultado expuesto, aprender detalladamente el paso a paso de cada modelo de fiabilidad, es una tarea fundamental para su correcta y efectiva aplicación. Diversas investigaciones reservan el proceso de resolución y solo presentan resultados finales indicando el uso de algún modelo, o bien el uso de una herramienta informática. Es por esta razón que esta investigación presentó un procedimiento analítico y explicativo sobre la definición, metodología de cálculo y criterios que deben ser considerados para parametrizar activos industriales bajo cierto nivel de degradación post mantenimiento, completando además su análisis con una aplicación numérica que permite evidenciar paso a paso el desarrollo matemático y estocástico según corresponda. Por medio de este tipo de análisis, las áreas de gestión y planificación se verán favorecidas en la medida que el activo está correctamente diagnosticado y, por supuesto, si el análisis e interpretación de resultados está bien hecho. Con esto es posible estimar, proyectar y simular diferentes escenarios de desempeño de los activos y su consecuente resultado en el negocio.

Los resultados dos, tres, cuatro y cinco están alineados con un objetivo equivalente, que principalmente es la creación de herramientas gráficas de soporte para la gestión de mantenimiento y operaciones, y sus procesos de toma de decisión. El diseño de cada una de estas propuestas responde a requerimientos específicos (preguntas de interés) presentados en cada desafío, vinculados principalmente con el diagnóstico temprano de patrones y tendencias de comportamiento de los activos, control y monitoreo de indicadores de desempeño (básicos, avanzados y/o de efectividad global), y la búsqueda permanente de fenómenos de riesgo atribuibles a una incorrecta gestión tanto del mantenimiento como de la operación.

Cada una de las herramientas expuestas ha sido implementada en la industria, por lo cual es importante mencionar recomendaciones para su exitosa aplicación:

- Recopilación de las fuentes de datos disponibles que aseguren la información mínima requerida por cada herramienta. Idealmente se debe tener el soporte de sistemas informáticos. Se recomienda al menos 3 meses de datos históricos.
- Definición de los procesos y protocolos de captura, validación y depuración de los datos a utilizar para el análisis.

- Diseño y cálculo de indicadores básicos de desempeño, alineados a los intereses de la gerencia. Se requiere la involucración de las jefaturas para el diseño y planificación de trabajo y su implementación.
- Utilizar el Excel como herramienta de programación prototipo. Una vez que se ha validado la herramienta y los usuarios conocen perfectamente sus bondades, se recomienda optar por invertir en una solución de mayor sofisticación informática.
- Análisis de resultados con equipos de multidisciplinarios y por medio de reuniones participativas.

Generalmente, GAMM, GAOM y GAOEM son aplicables a nivel de elemento mantenible/reemplazable, o a nivel agregado (sistema). No obstante, su aplicación y efectividad dependerá del nivel de información disponible y del tipo de análisis que desee desarrollarse. Por ejemplo, pensando en la herramienta GAMM, si se desea analizar un equipo a nivel de modo de fallo, lo ideal sería trabajar a nivel de un elemento básico (equipo), y posteriormente sumergirse en los modos de fallo que sean identificados como crónicos y/o agudos dentro del macro análisis. Para el caso de GAOM, como el interés fundamental es la producción, lo ideal sería implementarlo sobre un equipo en serie, o bien a la salida de una línea de producción. Bajo este escenario, habría que complementar el análisis con otras herramientas de reportabilidad y criticidad, como es caso de Pareto y diagramas de dispersión con foco en la frecuencia de fallo y en los tiempos fuera de servicio (Knights, 2001). GAOEM, con foco en la efectividad global, es flexible 100% al nivel de agregación que desee el usuario. Sin embargo, la evidencia empírica indica que los indicadores de efectividad son deseados fundamentalmente a nivel agregado, sea una línea, un sistema o proceso total.

Como investigación futura, existe un gran potencial para la automatización de estas herramientas utilizando lenguajes de programación avanzados que permiten su implementación en sistemas de planificación de recursos empresariales. Por lo tanto, en contextos con gran cantidad de datos, esta herramienta puede contribuir de manera importante a tener un enfoque sistemático e inteligente para capturar, gestionar y analizar datos, con el fin de obtener conocimientos especializados para tomar decisiones. Estas propuestas podemos visualizarlas en el entorno de un "Cyber-Physical Systems" (Lee et. al, 2015), que puede utilizarse para abordar estos problemas en la industria actual, proporcionando capacidades autónomas de control, autoconocimiento y autogestión a las máquinas industriales.

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ANEXO 1: REPORTE CONFIABILIDAD INTEGRAL

1 Datos Generales

Cliente	**Minera Antucoya**		
Preparado por:		Fecha de Emisión	Noviembre de 2016

2 Introducción

N°	Descripción
1	Análisis RAM de Equipos Críticos Faena Minera Antucoya

3 Desarrollo

3.1 Proceso

La selección de los equipos para el Reporte de Confiabilidad se basará en el análisis de las horas impactadas en la planta. De esta manera se asume como criterio relevante la configuración lógico funcional de cada equipo. Luego se realiza un análisis RAM a el (los) equipo (s) seleccionado (s) y se vincula el desempeño específico con el seguimiento de las acciones de mejora que se han propuesto. Finalmente se concluye con el nivel de cumplimiento de los planes de acción y la identificación de la efectividad de las actividades incluidas en dichos planes.

3.2 Alcance

El periodo de análisis será trimestral y se hará un barrido de todos los equipos diagramados en planta. Se compararán dos periodos trimestrales cerrados, cada uno con tiempo nominal de 2184 [hr].

El presente reporte de Confiabilidad abarca los trimestres:

- Trimestre 2: Abril, Mayo y Junio.
- Trimestre 3: Julio, Agosto y Septiembre.

3.3 Metodología

- Definir equipos críticos por trimestre a través de análisis de Pareto de mantenciones no programadas (MNP) impactados.

- Jerarquizar los modos de fallas mediante un análisis Jack Knife obteniendo los modos de fallas críticos.

- Analizar la gestión del mantenimiento de los equipos seleccionados mediante gráficos GAMM, a partir del software RelPro.

- Proponer mejoras y seguimiento de resultados en la gestión del mantenimiento del equipo.

3.4 Consideraciones y Reglas de Lectura

- La base de datos fue modificada eliminando el modo de falla “Mantención sobre programada” para luego obtener los valores a partir de los reportes exportados desde el Software RelPro.

- Los valores de los tiempos de Mantención No Programados impactados se obtuvieron a partir del Reporte Pareto incluido en el Software RelPro, aplicándole luego a los equipos fraccionados factores de impacto de acuerdo a su configuración lógico funcional.

- En los gráficos Jack Knife de cada trimestre se incluyeron los 20 modos de falla con mayor duración.

- Las curvas de iso indisponibilidad de A= 0,997, A=0,995, A=0,993 corresponden a indisponibilidades causadas por 5 [hr], 10 [hr] y 15 [hr] con respecto al total de horas nominales del trimestre 2184 [hr], respectivamente.

- El gráfico Jack Knife Trimestre 2 v/s Trimestre 3, presenta en tonos azules el trimestre 2 y en tonos rojos trimestre 3. Además presenta las mismas curvas de iso indisponibilidad en tonos grises.

- Los cuadrantes del Gráfico Jack Knife indican la criticidades de los modos de fallas:
    - **Cuadrante Agudo (superior izquierdo)**: Son fallas que se repiten poco, pero que tardan mucho en repararse. Representa problemas de mantenibilidad.
    - **Cuadrante Crónico (inferior derecho)**: Son fallas repetitivas y fáciles de reparar. Representa problemas de confiabilidad.
    - **Cuadrante Agudo & Crónico (superior derecho)**: Son fallas recurrentes y de gran complejidad para reparar. Representa problemas de disponibilidad. Se consideran modos de fallas críticos.
    - **Cuadrante Bajo Control (inferior izquierdo):** Son fallas poco habituales y fáciles de reparar.

- La numeración de los modos de falla de los equipos a estudiar está de acuerdo a un listado, el cual le asigna un único código para ambos trimestres.

- Los gráficos GAMM consideran todos los modos de fallas MNP y MP tomados como detenciones generales de toda la planta, en cada trimestre.

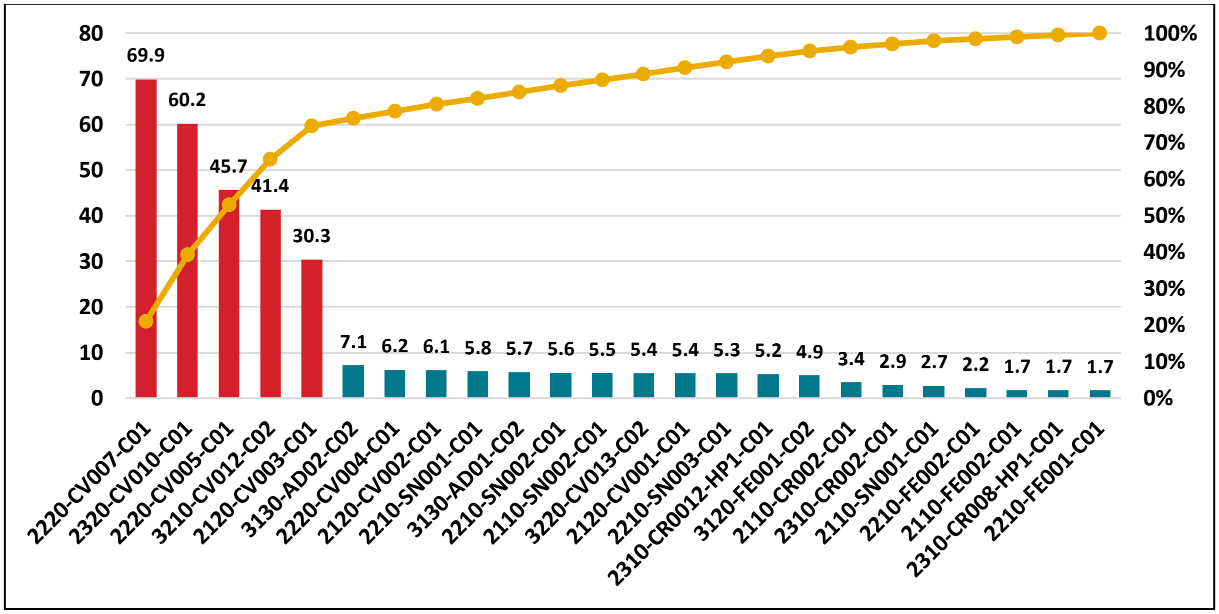
- Los gráficos GAMM en el eje vertical presentan el número acumulado de intervenciones, mientras que en el eje horizontal el tiempo calendario. El diámetro de la burbuja representa a escala aproximada el valor del TTR de la intervención. Las intervenciones se muestran en color azul para mantenciones preventivas (Mantención Gral. Planta) y en rojo para mantención correctiva (imprevistos).

- Los gráficos GAMM en el eje horizontal muestran el tiempo calendario a intervalos de semanas de 168 [h] a partir del 01-04-2016 (2184 [hr]) hasta el 01-07-2016 (4368 [hr]) para el Trimestre 2, para luego mostrar en el Trimestre 3 a partir del 01-07-2106 (4368 [hr]) hasta el 01-10-2016 (6576 [hr]).

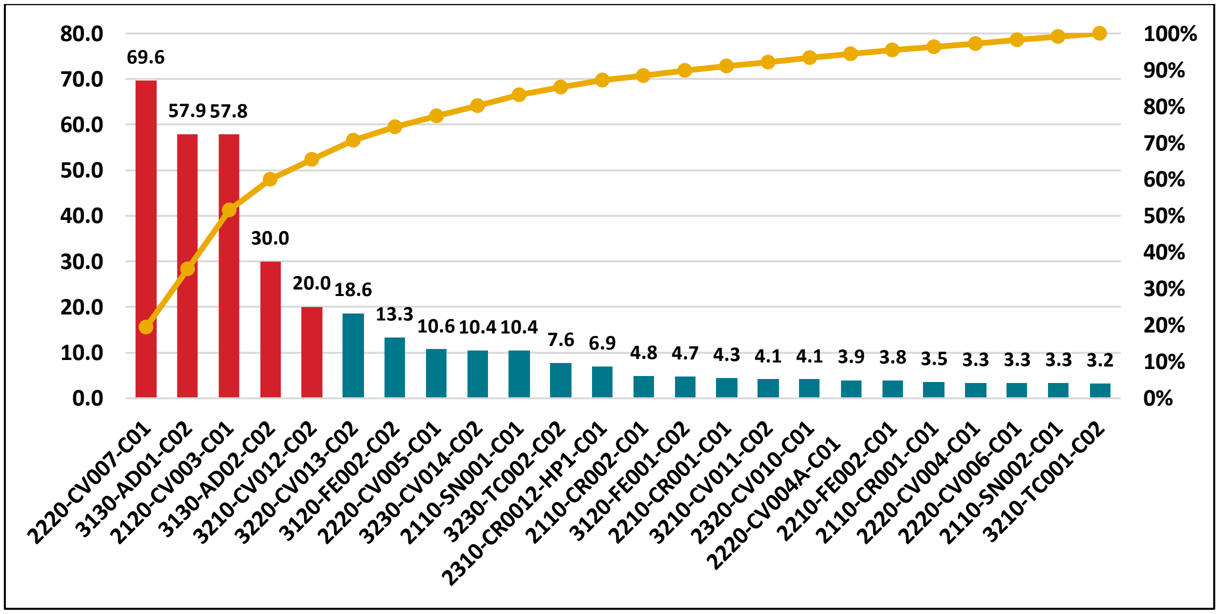
- El indicador MTTF post PM representa el promedio de duración desde el comienzo de una Mantención Preventiva PM hasta la primera falla del equipo.

4 Jerarquización Equipos a analizar

4.1 Pareto de Modos MNP Impactados - Trimestre 2 [Abril-Mayo-Junio]



4.2 Pareto de Modos MNP Impactados –Trimestre 3 [Julio-Agosto-Septiembre]



Observaciones:

- Se distingue que la correa CV007 es el equipo más indisponible de la planta en ambos trimestres, por lo que es el primer equipo que se aplicará análisis.
- El segundo equipo a evaluar es la correa CV003 ya que subió su tiempo indisponible a aproximadamente el doble desde trimestre 2 a trimestre 3.
- El tercer equipo a evaluar es el tambor Aglomerador AD01 ya que subió su tiempo indisponible x10 desde el trimestre 2 a trimestre 3.

5 Observaciones Análisis RAM

5.1 Análisis General 2220-CV007-C01

Se evidencian mejoras y empeoramiento de ciertos componentes del Carro Móvil. Las mejoras con respecto a los moto reductores y el empeoramiento con relación a los sensores de localización.

Se mantienen alta frecuencia y duración de detenciones asociadas al daño en canto de la cinta transportadora.

Se observan cambios en la duración de las mantenciones preventivas pero manteniendo los intervalos entre ellas. Sin embargo, los cambios significaron una disminución leve del número de intervenciones correctivas.

En el Trimestre 3 se observan acumulación de mantenciones correctivas inmediatamente después de mantenciones preventivas (hasta 5 [hr] post MP). Lo anterior ocurre en 3 de las 12 mantenciones preventivas del trimestre. El MTTF post MP del trimestre es 41,79 [hr] y MTTR de 0,93 [hr]. En promedio hay 4,46 fallas entre mantenciones preventivas del equipo. Por otro lado, las intervenciones de mantenimiento correctivo presentan un MTTR para el trimestre 3 de 1,22 [hr] mayor al trimestre 2, con desviación estándar de 1,92 [hr].

En conclusión las detenciones asociadas al carro móvil disminuyen principalmente por los moto reductores pero aumentan las detenciones asociadas a la cinta transportadora. Por otro lado, se presentan fallas catastróficas asociadas al riel del carro móvil. Además, se evidencia desaparición de las detenciones asociadas al raspador y acoplamiento hidráulico.

5.2 Análisis General 2120-CV003-C01

Se evidencian mejoras y empeoramiento de ciertos componentes del Carro Móvil. Las mejoras con respecto a los moto reductores y el empeoramiento asociado freno de aparcamiento y detenciones en un sentido el cual se soluciona parcialmente mediante un manejo operacional del equipo, que aún no es evidenciado la causa raíz.

Se mantienen las detenciones asociadas en Guarderas del equipo, Estación de Polines y Daños en la cinta transportadora.

En el Trimestre 3 no se observa acumulación de mantenciones correctivas inmediatamente posterior de mantenciones preventivas (hasta 5 [hr] post MP) a excepción de la última mantención preventiva. El MTTF post MP de 37,75 [hr] y MTTR de 1,4 [hr]. Por otro lado, el MTTR de las intervenciones correctivas del trimestre fue de 1,0 [hr], con desviación estándar de 1,551 [hr].

En conclusión, se evidencian problemas de confiabilidad debido a las detenciones asociadas al carro móvil y de mantenibilidad en relación a la reparación de reductor.

5.3 Análisis General 3130-AD01-C02

Se evidencia empeoramiento en la confiabilidad (frecuencia de detenciones) del equipo asociado a los daños de Revestimiento Interior del Equipo. Del mismo modo, el Sistema de Lubricación del reductor aumenta su tiempo de indisponiblidad. Sin embargo, se evidencia una leve mejora en relación a las detenciones por falla de compresor disminuyendo su frecuencia pero aumento leve del tiempo indisponible.

En el Trimestre 3 no se observan acumulación de mantenciones correctivas inmediatamente después de mantenciones preventivas (hasta 5 [hr] post MP). El MTTF post PM es de 52,46 [hr] con un MTTR de 6,6 hrs, principalmente detenciones por las reparaciones de revestimiento interior del tambor. Por otro lado, el MTTR de las intervenciones correctivas del trimestre fue de 5,9 [hr], con desviación estándar de 15,55 [hr].

En conclusión, se mantienen problemas con el compresor pero baja su frecuencia. Por otro lado, se presenta problemas de mantenibilidad y calidad con respecto al revestimiento interior del tambor con alto MTTR y frecuencia. Lo anterior se expresa en el aumento del MTTR y desviación estándar del trimestre.

5.4 Observaciones Jack Knife 2220-CV007-C01 Trimestre 2 v/s Trimestre 3

5.4.1 Empeoramiento de Modos de Falla [-]

Modo de Falla	Movimiento Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF11] Daño en cinta transportadora	Se mantiene en cuadrante **Crónico**	MTTR 0,69 → 1,30 [hr] ↑ Frecuencia 16 → 15 [-] ↓	Tiempo 11,08 → 19,49 [hr] ↑	El MF11 se mantiene en cuadrante Crónico con un aumento en el MTTR, pero disminución en su frecuencia. Aumentó su tiempo indisponible. Este modo de falla se genera por lonjas en el costado derecho de la cinta por el funcionamiento con Desalineamiento.
[MF66] Falla del sensor de posición del carro móvil	Cuadrante **Crónico** a cuadrante **Agudo**	MTTR 0,34 → 4,80 [hr] ↑ Frecuencia 04 → 01 [-] ↓	Tiempo 1,34 → 4,80 [hr] ↑	El MF66 pasa de cuadrante Crónico a cuadrante Agudo con un aumento en el MTTR, pero disminución en su frecuencia. Aumento el tiempo indisponible. Este modo de falla se genera por problemas en el sistema de localización del carro móvil.
[MF83] Falla sensor de velocidad cero	Cuadrante **Bajo Control** a cuadrante **Crónico**	MTTR 1,0 → 0,2 [hr] ↑ Frecuencia 01 → 03 [-] ↓	Tiempo 1,0 → 0,60 [hr] ↑	El MF83 pasa de cuadrante Bajo Control a cuadrante Crónico con una disminución en el MTTR, pero aumento en su frecuencia. Disminuyó su tiempo indisponible.
[MF07] Carro Fuera de Posición	Aparece en cuadrante **Agudo**	MTTR 9,29 [hr] Frecuencia 02 [-]	Tiempo 18,59 [hr]	El MF07 aparece en cuadrante Agudo con alto MTTR y baja frecuencia. Genera un alto tiempo indisponible. Este modo de falla se genera al salirse el carro móvil del riel y el alto MTTR es debido a las actividades de mantenimiento necesarias para retomar a su posición.
[MF79] Falla sensor de límite de seguridad	Aparece en cuadrante **Crónico**	MTTR 0,2 [hr] Frecuencia 03 [-]	Tiempo 0,60 [hr]	El MF79 aparece en cuadrante Crónico con bajo MTTR y alta frecuencia. Este modo de falla se genera al quedarse el sensor en posición accionado.

5.4.2 Mejoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF100] Falla de motor del motoreductor	Cuadrante **Agudo & Crónico** a cuadrante **Bajo Control**	MTTR 1,17 → 0,64 [hr] ↑ Frecuencia 06 → 02 [-] ↓	Tiempo 7,02 → 1,28 [hr] ↓	El MF100 pasa de cuadrante Agudo & Crónico a cuadrante Bajo Control con una disminución tanto en el MTTR como en la frecuencia. Este modo de falla se le aplicó un RCA.
[MF56] Rotura/Fuga de chute	Cuadrante **Crónico** a cuadrante **Bajo Control**	MTTR 0,58 → 0,75 [hr] ↑ Frecuencia 04 → 02 [-] ↓	Tiempo 2,30 → 1,49 [hr] ↓	El MF56 pasa de cuadrante Crónico a cuadrante Bajo Control con una disminución de la frecuencia pero aumento en su MTTR. Este modo de falla se controló mediante un ingeniero de desgaste.
[MF03] Alta Temperatura	Desaparece de cuadrante **Agudo &**	MTTR 1,63 [hr] Frecuencia	Tiempo 4,88 [hr]	El MF03 desaparece desde cuadrante Agudo & Crónico.

Acoplamiento Hidráulico	**Crónico**	03 [-]		
[MF39] Falla raspador cinta	Desaparece de cuadrante **Agudo & Crónico**	MTTR 1,17 [hr] Frecuencia 03 [-]	Tiempo 3,52 [hr]	El MF39 desaparece desde cuadrante Agudo & Crónico.

5.5 Observaciones Jack Knife 2120-CV003-C01 Trimestre 2 v/s Trimestre 3

5.5.1 Empeoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF33] Falla o ajuste de Guardera	Cuadrante **Agudo** a cuadrante **Agudo & Crónico**	MTTR 4,55 → 1,83 [hr] ↓ Frecuencia 01 → 07 [-] ↑	Tiempo 4,55 → 12,80 [hr] ↑	El MF33 pasa de cuadrante Agudo a cuadrante Agudo & Crónico con una disminución en el MTTR, pero aumento en su frecuencia. Aumento el tiempo indisponible.
[MF11] Daño en cinta transportadora	Se mantiene en cuadrante **Agudo**	MTTR 0,93 → 4,14 [hr] ↑ Frecuencia 01 → 02 [-] ↑	Tiempo 0,93 → 8,29 [hr] ↑	El MF11 se mantiene en cuadrante Agudo con un aumento en el MTTR y aumento en su frecuencia. Aumento el tiempo indisponible.
[MF29] Falla freno aparcamiento carro móvil	Se mantiene en cuadrante **Agudo**	MTTR 1,68 → 3,59 [hr] ↑ Frecuencia 01 → 01 [-]	Tiempo 1,68 → 3,59 [hr] ↑	El MF29 se mantiene en cuadrante Agudo con un aumento en el MTTR, pero manteniendo su frecuencia. Aumento el tiempo indisponible.
[MF27] Falla estación de polines	Cuadrante **Bajo Control** a cuadrante **Agudo**	MTTR 0,47 → 3,31 [hr] ↑ Frecuencia 02 → 01 [-] ↑	Tiempo 0,93 → 3,31 [hr] ↑	El MF27 pasa de cuadrante Bajo Control a Cuadrante Agudo con un aumento en el MTTR pero disminución en frecuencia. Genera un alto tiempo indisponible.
[MF40] Falla reductor	Aparece en cuadrante **Agudo & Crónico**	MTTR 3,26 [hr] Frecuencia 04 [-]	Tiempo 13,02 [hr]	El MF40 aparece en cuadrante Agudo & Crónico con alto MTTR y alta frecuencia. Genera un alto tiempo indisponible.
[MF38] Falla Polines	Aparece en cuadrante **Crónico**	MTTR 0,90 [hr] Frecuencia 04 [-]	Tiempo 3,61 [hr]	El MF38 aparece en cuadrante Crónico con bajo MTTR y alta frecuencia. Genera un alto tiempo indisponible.
[MF121] Otro mecánico (detención CM)	Aparece en cuadrante **Crónico**	MTTR 0,11 [hr] Frecuencia 12 [-]	Tiempo 1,28 [hr]	El MF121 aparece en cuadrante Crónico con bajo MTTR, por con alta frecuencia. El tiempo indisponible no es alto en comparación con los demás modos de falla pero genera problemas de confiabilidad en el equipo.

5.5.2 Mejoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF100] Falla de motor del motoreductor	Cuadrante **Agudo & Crónico** a cuadrante **Bajo Control**	MTTR 0,75 → 0,33 [hr] ↓ Frecuencia 04 → 02 [-] ↓	Tiempo 3,02 → 0,67 [hr] ↓	El MF100 pasa de cuadrante Agudo & Crónico a cuadrante Bajo Control con una disminución tanto en el MTTR como en la frecuencia. Este modo de falla se le aplicó un RCA.
MF[118] Otros instrumentación (sobre carrera)	Cuadrante **Crónico** a cuadrante **Bajo Control**	MTTR 0,13 → 0,28 [hr] ↑ Frecuencia 05 → 01 [-] ↓	Tiempo 0,64 → 0,28 [hr] ↓	El MF118 pasa de cuadrante Crónico a cuadrante Bajo Control con un aumento en el MTTR pero disminución en la frecuencia.
[MF56] Rotura/Fuga Chute	Desaparece de cuadrante **Agudo**	MTTR 2,86 [hr] Frecuencia 02 [-]	Tiempo 5,73 [hr]	El MF56 pasa de cuadrante Crónico a cuadrante Bajo Control con una disminución de la frecuencia pero aumento en su MTTR. Este modo de falla se controló mediante un ingeniero de desgaste.
[MF101] Falla de motor eléctrico	Desaparece de cuadrante **Crónico**	MTTR 0,32 [hr] Frecuencia 05 [-]	Tiempo 1,60 [hr]	El MF101 desaparece desde cuadrante Agudo & Crónico.
[MF66] Falla Del sensor de posición del carro móvil	Desaparece de cuadrante **Crónico**	MTTR 0,13 [hr] Frecuencia 03 [-]	Tiempo 0,38 [hr]	El MF66 desaparece desde cuadrante Agudo & Crónico.
[MF32] Falla frenos electromagnético del motoreductor (MEC)	Desaparece de cuadrante **Crónico**	MTTR 0,09 [hr] Frecuencia 03 [-]	Tiempo 0,28 [hr]	El MF32 desaparece desde cuadrante Crónico.

5.6 Observaciones Jack Knife 3130-AD01-C02 Trimestre 2 v/s Trimestre 3

5.6.1 Empeoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF12] Daño de revestimiento interior del tambor	Aparece en cuadrante **Agudo & Crónico**	MTTR 22,69 [hr] Frecuencia 05 [-]	Tiempo 113,46 [hr]	El MF12 aparece en cuadrante Agudo & Crónico con alto MTTR y alta frecuencia. Genera un alto tiempo indisponible.
[MF46] Sistema de lubricación de reductor	Se mantiene en cuadrante **Crónico**	MTTR 0,19 → 0,67 [hr] ↑ Frecuencia 03 → 03 [-]	Tiempo 0,57 → 2,01 [hr] ↑	El MF46 se mantiene en cuadrante Crónico con un aumento en el MTTR, pero manteniendo su frecuencia. Aumento el tiempo indisponible.
[MF13] Daño estructural (MEC)	Aparece en cuadrante **Agudo**	MTTR 10,33 [hr] Frecuencia 01 [-]	Tiempo 10,33 [hr]	El MF13 aparece en cuadrante Agudo con alto MTTR y baja frecuencia. Genera un alto tiempo indisponible.

5.6.2 Mejoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF78] Falla compresor	Se mantiene en cuadrante **Crónico**	MTTR 0,12 → 0,22 [hr] ↑ Frecuencia 09 → 05 [-] ↓	Tiempo 1,05 → 1,09 [hr] ↑	El MF78 pasa se mantiene en cuadrante Crónico con un aumento en el MTTR pero disminución en la frecuencia. Aumenta levemente su tiempo indisponible.

6 Resumen de Cumplimiento de Planes de Acción

Los modos de falla analizados a partir del Gráfico Jack Knife y luego revisados junto al equipo en el reporte GAMM, se presentan para seguimiento a partir del cumplimiento de los planes de acción Amenazas y Top-Ten propuestos en la Planilla TOP-TEN.

6.1.1 Correa 2220-CV007-C01

Modo de Falla	Planes de Acción Asociados	% Cumplimiento
[MF11] **Daño en cinta transportadora**	Amenazas 6, 32 y 40	100%
[MF66] **Falla del sensor de posición del carro móvil**	Amenazas 9	80%
[MF83] **Falla sensor de velocidad cero**	Sin plan de acción	-
[MF07] **Carro Fuera de Posición**	Amenazas 147, 148 y 149	87%
[MF79] **Falla sensor de límite de seguridad**	Sin plan de acción	-

6.1.2 Correa 2120-CV003-C01

Modo de Falla	Planes de Acción Asociados	% Cumplimiento
[MF33] **Falla o ajuste de Guardera**	Amenazas 100 y 128	100%
	Top Ten 12	80%
[MF66] **Falla del sensor de posición del carro móvil**	Amenazas 9	80%
[MF11] **Daño en cinta transportadora**	Amenazas 32	100%
[MF29] **Falla freno aparcamiento carro móvil**	Amenazas 140	60%
[MF38] **Falla reductor**	Amenazas 113 y 114	50%
[MF121] **Otro mecánico (detención CM)**	Amenazas 156	50%
[MF27] **Falla estación de Polines**	Amenazas 50 y 83	100%

6.1.3 Tambor Aglomerador 3130-AD001-C02

Modo de Falla	Planes de Acción Asociados	% Cumplimiento
[MF12] **Daño de revestimiento interior del tambor**	Amenazas 133, 142, 143, 144, 145 y 163	100%
[MF46] **Sistema de lubricación de reductor**	Sin plan de acción	-
[MF13] **Daño estructural (MEC)**	Amenazas 32	-
[MF78] **Falla compresor**	Amenazas 140	75%

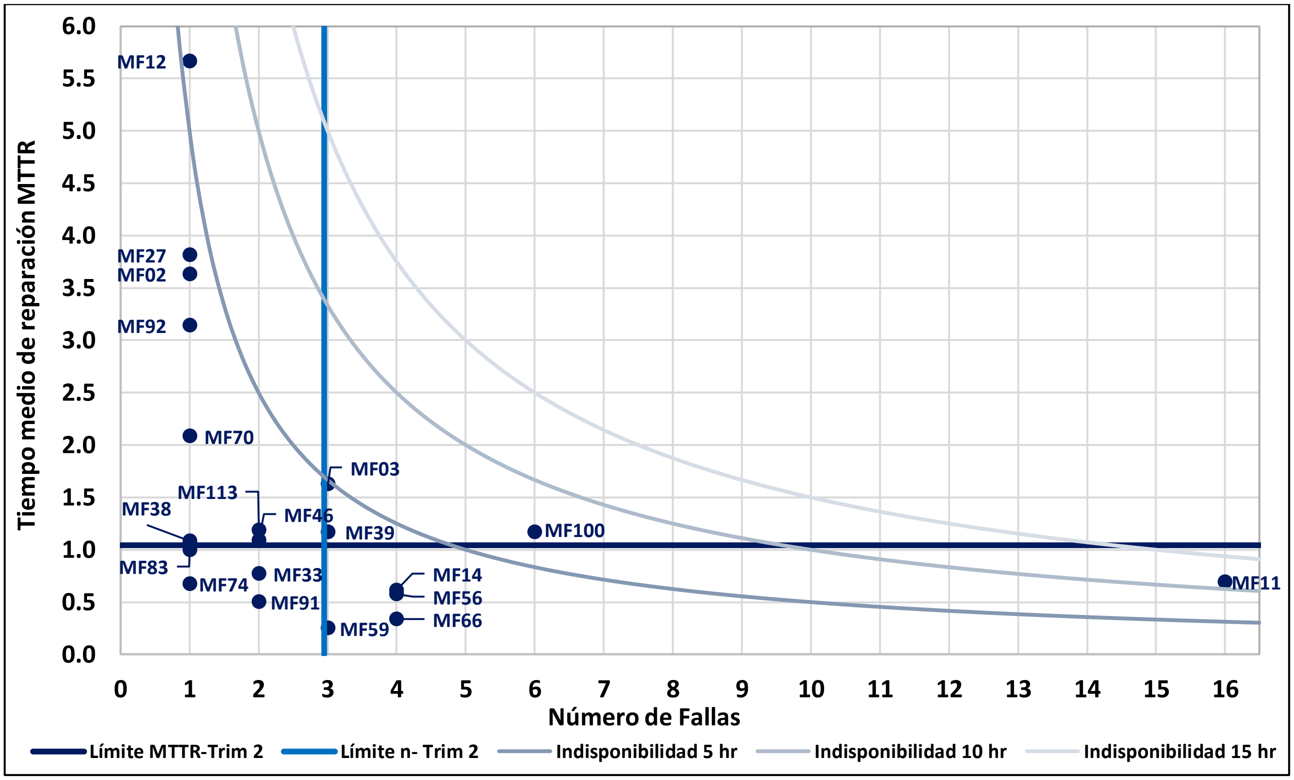
7 Análisis RAM detallado

7.1 Análisis Jack Knife Equipos

7.1.1 Análisis 2220-CV007-C01

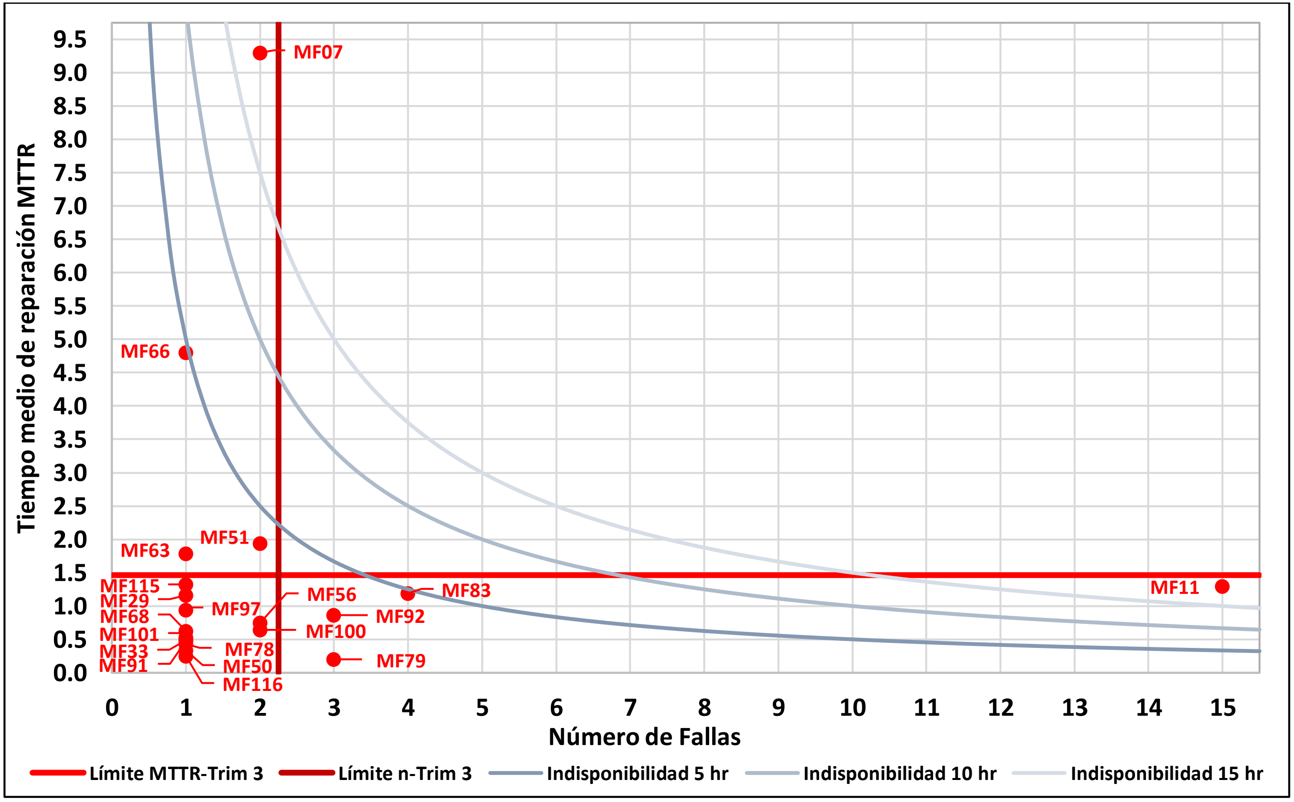
7.1.1.1 Jack Knife 2220-CV007-C01 Trimestre 2 [Abril-Mayo-Junio]

Modo de Falla	Modos de Falla (MF)	N° MF	n	MTTR	Dur
Fallas Agudas&Crónicas					
Falla de Motor del motoreductor	2220-CV007-C01-MF100	MF100	6	1,17	7,02
Alta Temperatura Acoplamiento Hidráulico	2220-CV007-C01-MF03	MF03	3	1,63	4,88
Falla Raspador Cinta	2220-CV007-C01-MF39	MF39	3	1,17	3,52
Fallas Crónicas					
Daño en Cinta Transportadora	2220-CV007-C01-MF11	MF11	16	0,69	11,08
Desalineamiento de Correa (MEC)	2220-CV007-C01-MF14	MF14	4	0,61	2,46
Rotura/Fuga en Chute	2220-CV007-C01-MF56	MF56	4	0,58	2,30
Falla del Sensor de Posición del Carro Móvil	2220-CV007-C01-MF66	MF66	4	0,34	1,34
Activación sensor de estiramiento	2220-CV007-C01-MF59	MF59	3	0,25	0,75
Fallas Agudas					
Daño estructural (MEC)	2220-CV007-C01-MF12	MF12	1	5,67	5,67
Falla Estación de Polines	2220-CV007-C01-MF27	MF27	1	3,82	3,82
Ajuste cajón guiador de alimentación	2220-CV007-C01-MF02	MF02	1	3,63	3,63
Corte de Energía	2220-CV007-C01-MF92	MF92	1	3,14	3,14
Falla encoder	2220-CV007-C01-MF70	MF70	1	2,08	2,08
Sobre Corriente Motor	2220-CV007-C01-MF113	MF113	2	1,19	2,38
Fuga de aceite Acoplamiento Hidráulico	2220-CV007-C01-MF46	MF46	2	1,09	2,18
Falla Polines	2220-CV007-C01-MF38	MF38	1	1,08	1,08
Fallas Bajo Control					
Falla o ajuste de Guardera	2220-CV007-C01-MF33	MF33	2	0,77	1,54
Otro Instrumentación	2220-CV007-C01-MF91	MF91	2	0,50	1,01
Falla Sensor Velocidad Cero	2220-CV007-C01-MF83	MF83	1	1,00	1,00
Falla pull cord	2220-CV007-C01-MF74	MF74	1	0,68	0,68

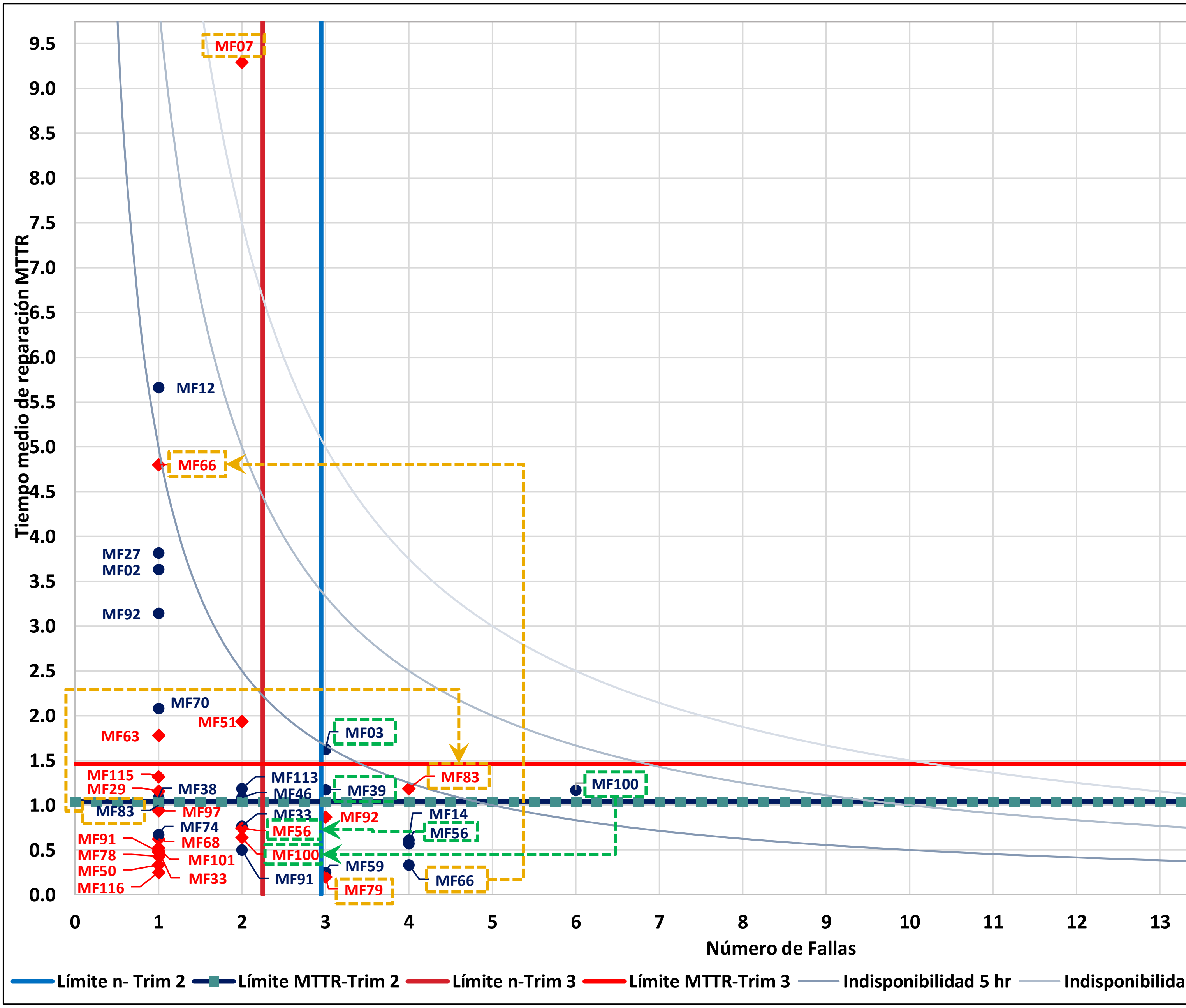

Tiempo medio de reparación MTTR
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Número de Fallas
MF12
MF27
MF02
MF92
MF70
MF03
MF113
MF38
MF46
MF39
MF100
MF83
MF74
MF33
MF91
MF59
MF14
MF56
MF66
MF11
Límite MTTR-Trim 2
Límite n- Trim 2
Indisponibilidad 5 hr
Indisponibilidad 10 hr
Indisponibilidad 15 hr

7.1.1.2 Jack Knife 2220-CV007-C01 Trimestre 3 [Julio-Agosto-Septiembre]

Modo de Falla	Modos de Falla (MF)	N° MF	n	MTTR	Dur.
Fallas Agudas&Crónicas					
Fallas Crónicas					
Daño en Cinta Transportadora	2220-CV007-C01-MF11	MF11	15	1,30	19,49
Falla Sensor Velocidad Cero	2220-CV007-C01-MF83	MF83	4	1,19	4,74
Corte de Energía	2220-CV007-C01-MF92	MF92	3	0,87	2,60
Falla Sensor de Limite de Seguridad	2220-CV007-C01-MF79	MF79	3	0,20	0,60
Fallas Agudas					
Carro Fuera de Posición	2220-CV007-C01-MF07	MF07	2	9,29	18,59
Falla del Sensor de Posición del Carro Móvil	2220-CV007-C01-MF66	MF66	1	4,80	4,80
Inspección de equipo (MEC)	2220-CV007-C01-MF51	MF51	2	1,94	3,88
Falla Comunicación	2220-CV007-C01-MF63	MF63	1	1,78	1,78
Fallas Bajo Control					
Rotura/Fuga en Chute	2220-CV007-C01-MF56	MF56	2	0,75	1,49
Otro mecánico (Acople Dañado por fierro enrollado)	2220-CV007-C01-MF115	MF115	1	1,32	1,32
Falla de Motor del motoreductor	2220-CV007-C01-MF100	MF100	2	0,64	1,28
Falla Freno Aparcamiento Carro Móvil	2220-CV007-C01-MF29	MF29	1	1,16	1,16
Falla conexión eléctrica	2220-CV007-C01-MF97	MF97	1	0,94	0,94
Falla en parada de emergencia	2220-CV007-C01-MF68	MF68	1	0,63	0,63
Falla de motor eléctrico	2220-CV007-C01-MF101	MF101	1	0,52	0,52
Falla o ajuste de Guardera	2220-CV007-C01-MF33	MF33	1	0,49	0,49
Otro Instrumentación	2220-CV007-C01-MF91	MF91	1	0,48	0,48
Falla Sensor Corte Correa	2220-CV007-C01-MF78	MF78	1	0,43	0,43
Inspección de Correa (MEC)	2220-CV007-C01-MF50	MF50	1	0,33	0,33
Otro Mecánico (Alta temperatura descanso)	2220-CV007-C01-MF116	MF116	1	0,25	0,25



7.1.1.3 Jack Knife 2220-CV007-C01 Trimestre 2 [Abril-Mayo-Junio] v/s Trimestre 3 [Julio-Agosto-Septiembre]



7.1.1.4 Observaciones Jack Knife 2220-CV007-C01 Trimestre 2 v/s Trimestre 3

Empeoramiento de Modos de Falla [-]

Modo de Falla	Movimiento Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF11] Daño en cinta transportadora	Se mantiene en cuadrante **Crónico**	MTTR 0,69 → 1,30 [hr] ↑ Frecuencia 16 → 15 [-] ↓	Tiempo 11,08 → 19,49 [hr] ↑	El MF11 se mantiene en cuadrante Crónico con un aumento en el MTTR, pero disminución en su frecuencia. Aumentó su tiempo indisponible. Este modo de falla se genera por lonjas en el costado derecho de la cinta por el funcionamiento con Desalineamiento.
[MF66] Falla del sensor de posición del carro móvil	Cuadrante **Crónico** a cuadrante **Agudo**	MTTR 0,34 → 4,80 [hr] ↑ Frecuencia 04 → 01 [-] ↓	Tiempo 1,34 → 4,80 [hr] ↑	El MF66 pasa de cuadrante Crónico a cuadrante Agudo con un aumento en el MTTR, pero disminución en su frecuencia. Aumento el tiempo indisponible. Este modo de falla se genera por problemas en el sistema de localización del carro móvil.
[MF83] Falla sensor de velocidad cero	Cuadrante **Bajo Control** a cuadrante **Crónico**	MTTR 1,0 → 0,2 [hr] ↑ Frecuencia 01 → 03 [-] ↓	Tiempo 1,0 → 0,60 [hr] ↑	El MF83 pasa de cuadrante Bajo Control a cuadrante Crónico con una disminución en el MTTR, pero aumento en su frecuencia. Disminuyó su tiempo indisponible.
[MF07] Carro Fuera de Posición	Aparece en cuadrante **Agudo**	MTTR 9,29 [hr] Frecuencia 02 [-]	Tiempo 18,59 [hr]	El MF07 aparece en cuadrante Agudo con alto MTTR y baja frecuencia. Genera un alto tiempo indisponible. Este modo de falla se genera al salirse el carro móvil del riel y el alto MTTR es debido a las actividades de mantenimiento necesarias para retomar a su posición.
[MF79] Falla sensor de límite de seguridad	Aparece en cuadrante **Crónico**	MTTR 0,2 [hr] Frecuencia 03 [-]	Tiempo 0,60 [hr]	El MF79 aparece en cuadrante Crónico con bajo MTTR y alta frecuencia. Este modo de falla se genera al quedarse el sensor en posición accionado.

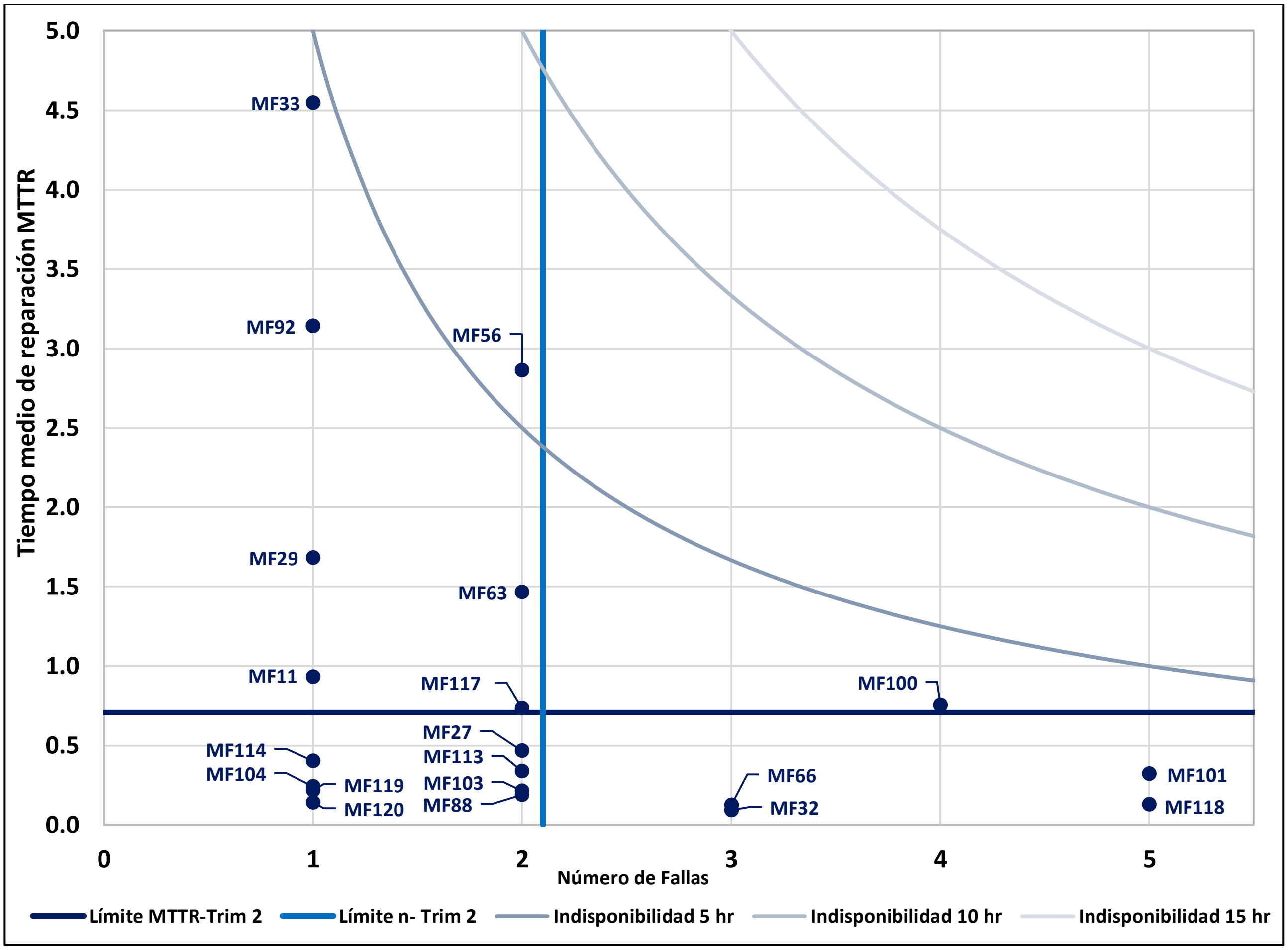
Mejoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF100] Falla de motor del motoreductor	Cuadrante **Agudo & Crónico** a cuadrante **Bajo Control**	MTTR 1,17 → 0,64 [hr] ↑ Frecuencia 06 → 02 [-] ↓	Tiempo 7,02 → 1,28 [hr] ↓	El MF100 pasa de cuadrante Agudo & Crónico a cuadrante Bajo Control con una disminución tanto en el MTTR como en la frecuencia. Este modo de falla se le aplicó un RCA.
[MF56] Rotura/Fuga de chute	Cuadrante **Crónico** a cuadrante **Bajo Control**	MTTR 0,58 → 0,75 [hr] ↑ Frecuencia 04 → 02 [-] ↓	Tiempo 2,30 → 1,49 [hr] ↓	El MF56 pasa de cuadrante Crónico a cuadrante Bajo Control con una disminución de la frecuencia pero aumento en su MTTR. Este modo de falla se controló mediante un ingeniero de desgaste.
[MF03] Alta Temperatura Acoplamiento Hidráulico	Desaparece de cuadrante **Agudo & Crónico**	MTTR 1,63 [hr] Frecuencia 03 [-]	Tiempo 4,88 [hr]	El MF03 desaparece desde cuadrante Agudo & Crónico.
[MF39] Falla raspador cinta	Desaparece de cuadrante **Agudo & Crónico**	MTTR 1,17 [hr] Frecuencia 03 [-]	Tiempo 3,52 [hr]	El MF39 desaparece desde cuadrante Agudo & Crónico.

7.1.2 Análisis 2120-CV003-C01

7.1.2.1 Jack Knife 2120-CV003-C01 Trimestre 2 [Abril-Mayo-Junio]

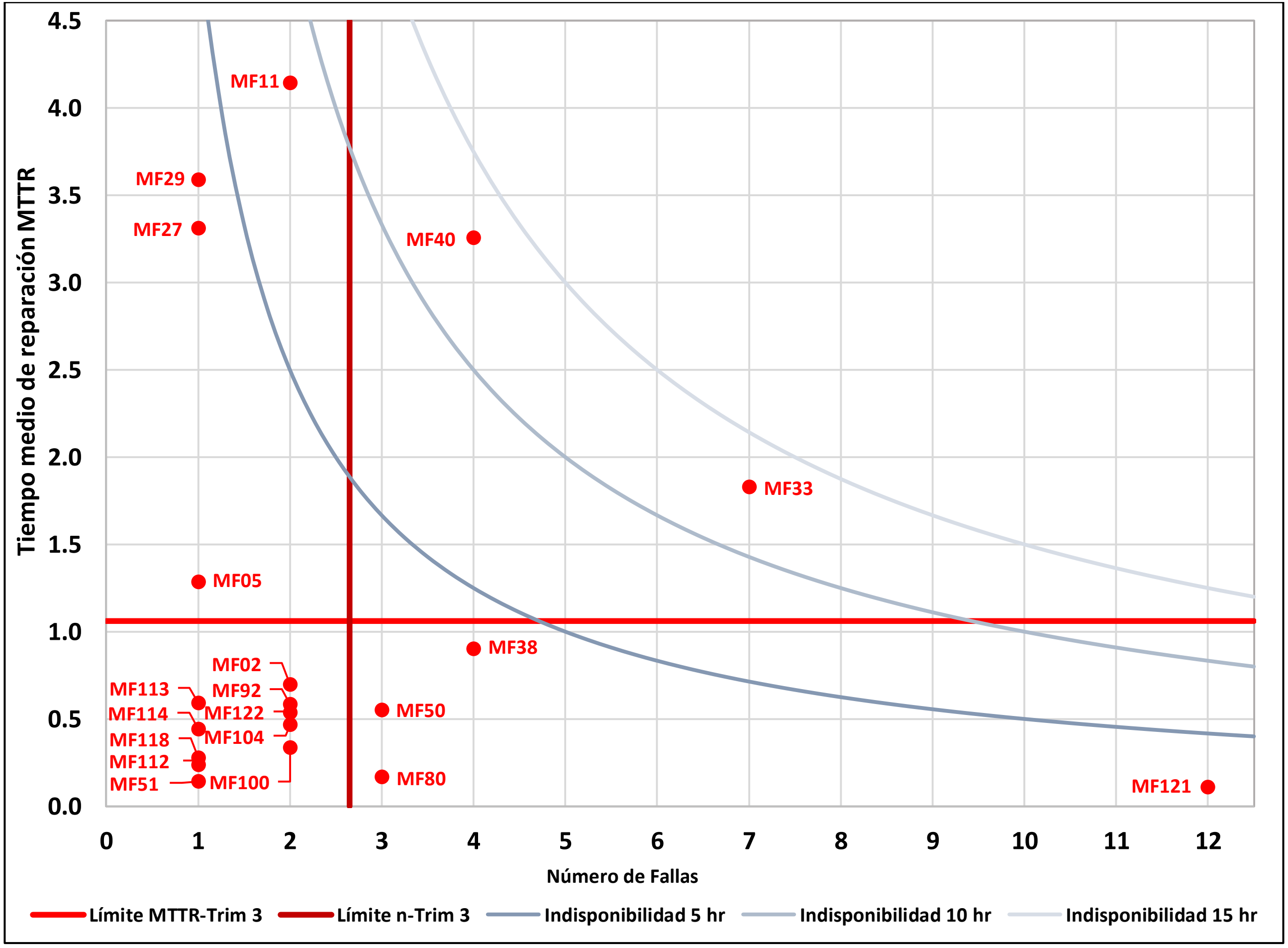
Modo de Falla	Modos de Falla (MF)	N° MF	n	MTTR	Dur
Fallas Agudas&Crónicas					
Falla de Motor del motoreductor	**2220-CV003-C01-MF100**	**MF100**	4	0,75	3,02
Fallas Crónicas					
Falla de motor eléctrico	**2220-CV003-C01-MF101**	**MF101**	5	0,32	1,60
Otro Instrumentación (sobrecarrera)	**2220-CV003-C01-MF118**	**MF118**	5	0,13	0,64
Falla del Sensor de Posición del Carro Móvil	**2220-CV003-C01-MF66**	**MF66**	3	0,13	0,38
Falla Frenos Electromagnético del motoreductor (MEC)	**2220-CV003-C01-MF32**	**MF32**	3	0,09	0,28
Fallas Agudas					
Rotura/Fuga en Chute	**2220-CV003-C01-MF56**	**MF56**	2	2,86	5,73
Falla o ajuste de Guardera	**2220-CV003-C01-MF33**	**MF33**	1	4,55	4,55
Corte de Energía	**2220-CV003-C01-MF92**	**MF92**	1	3,14	3,14
Falla comunicación	**2220-CV003-C01-MF63**	**MF63**	2	1,47	2,93
Falla freno aparcamiento carro móvil	**2220-CV003-C01-MF29**	**MF29**	1	1,68	1,68
Otro Eléctrico (falla partida)	**2220-CV003-C01-MF117**	**MF117**	2	0,73	1,47
Daño en Cinta Transportadora	**2220-CV003-C01-MF11**	**MF11**	1	0,93	0,93
Fallas Bajo Control					
Falla Estación de Polines	**2220-CV003-C01-MF27**	**MF27**	2	0,47	0,93
Sobre Corriente Motor	**2220-CV003-C01-MF113**	**MF113**	2	0,34	0,68
Falla Frenos Electromagnético del motoreductor (ELEC)	**2220-CV003-C01-MF103**	**MF103**	2	0,21	0,43
Sobre Corriente motoreductores	**2220-CV003-C01-MF114**	**MF114**	1	0,40	0,40
Falsa indicación	**2220-CV003-C01-MF88**	**MF88**	2	0,19	0,38
Falla Mecanismo Traslación Carro Móvil	**2220-CV003-C01-MF104**	**MF104**	1	0,24	0,24
Otro Mecánico (Falla partido equipo)	**2220-CV003-C01-MF119**	**MF119**	1	0,22	0,22
Otro Mecánico (Retiro guarderas)	**2220-CV003-C01-MF120**	**MF120**	1	0,14	0,14



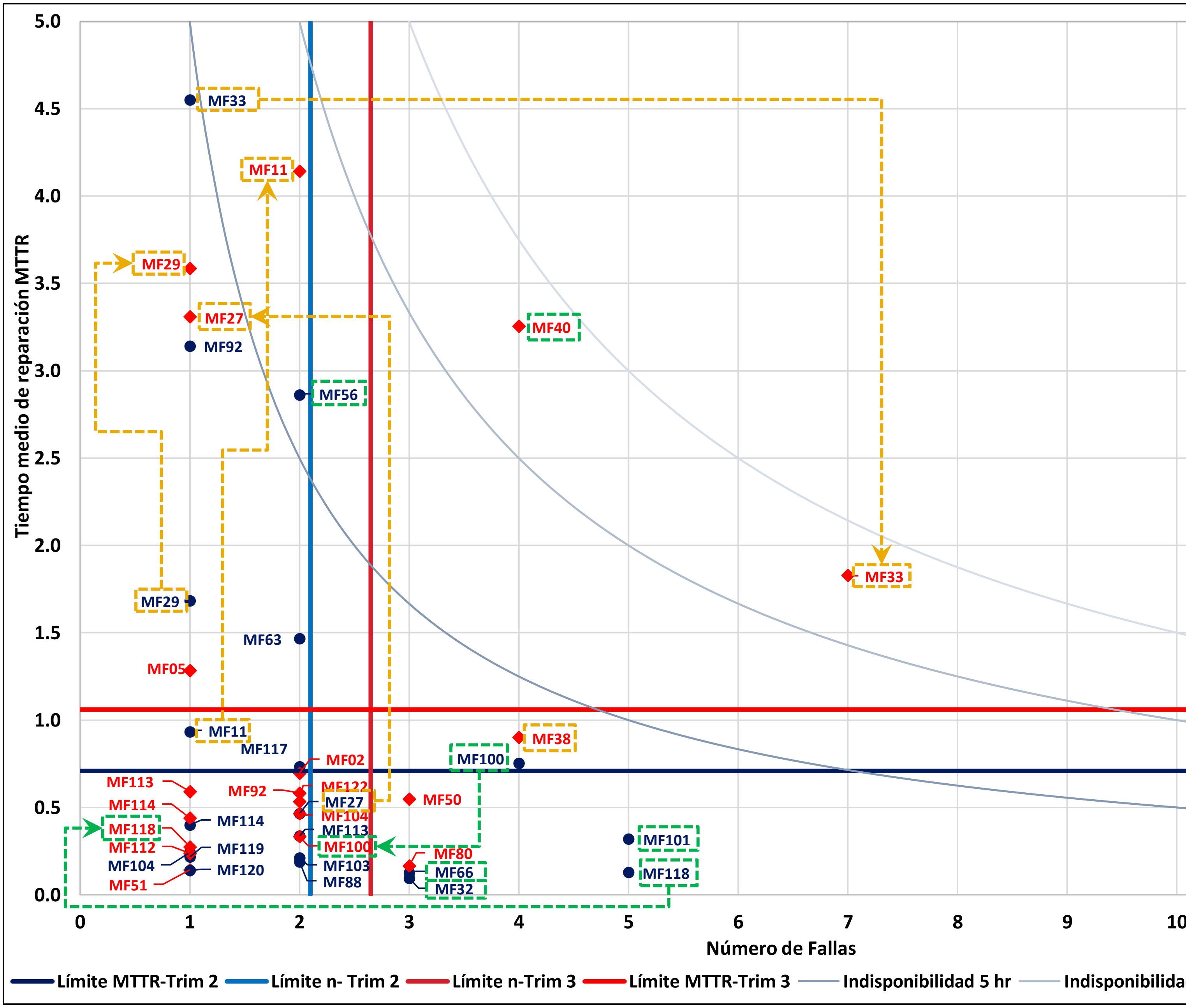
Tiempo medio de reparación MTTR
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
Número de Fallas
MF33
MF92
MF56
MF29
MF63
MF11
MF117
MF100
MF27
MF114
MF113
MF104
MF119
MF103
MF120
MF88
MF66
MF32
MF101
MF118
Límite MTTR-Trim 2
Límite n- Trim 2
Indisponibilidad 5 hr
Indisponibilidad 10 hr
Indisponibilidad 15 hr

7.1.2.2 Jack Knife 2120-CV003-C01 Trimestre 3 [Julio-Agosto-Septiembre]

Modo de Falla	Modos de Falla (MF)	N° MF	n	MTTR	Dur.
Fallas Agudas&Crónicas					
Falla Reductor	2220-CV003-C01-MF40	MF40	4	3,26	13,02
Falla o ajuste de Guardera	2220-CV003-C01-MF33	MF33	7	1,83	12,80
Fallas Crónicas					
Falla Polines	2220-CV003-C01-MF38	MF38	4	0,90	3,61
Inspección de Correa (MEC)	2220-CV003-C01-MF50	MF50	3	0,55	1,65
Otro Mecánico (detención CM)	2220-CV003-C01-MF121	MF121	12	0,11	1,28
Falla Sensor de Nivel	2220-CV003-C01-MF80	MF80	3	0,17	0,50
Fallas Agudas					
Daño en Cinta Transportadora	2220-CV003-C01-MF11	MF11	2	4,14	8,29
Falla Freno Aparcamiento Carro Móvil	2220-CV003-C01-MF29	MF29	1	3,59	3,59
Falla Estación de Polines	2220-CV003-C01-MF27	MF27	1	3,31	3,31
Caída Placa Chute Descarga	2220-CV003-C01-MF05	MF05	1	1,28	1,28
Fallas Bajo Control					
Ajuste cajón guiador de alimentación	2220-CV003-C01-MF02	MF02	2	0,70	1,39
Corte de Energía	2220-CV003-C01-MF92	MF92	2	0,58	1,17
Desviación Mant. Mec.(rebarbe reparación cinta)	2220-CV003-C01-MF122	MF122	2	0,53	1,07
Falla Mecanismo Traslación Carro Móvil	2220-CV003-C01-MF104	MF104	2	0,46	0,93
Falla de Motor del motoreductor	2220-CV003-C01-MF100	MF100	2	0,33	0,67
Sobre Corriente Motor	2220-CV003-C01-MF113	MF113	1	0,59	0,59
Sobre Corriente motoreductores	2220-CV003-C01-MF114	MF114	1	0,44	0,44
Otro Instrumentación (sobrecarrera)	2220-CV003-C01-MF118	MF118	1	0,28	0,28
Otro Eléctrico	2220-CV003-C01-MF112	MF112	1	0,24	0,24
Inspección de equipo (MEC)	2220-CV003-C01-MF51	MF51	1	0,14	0,14



7.1.2.3 Jack Knife 2120-CV003-C01 Trimestre 2 [Abril-Mayo-Junio] v/s Trimestre 3 [Julio-Agosto-Septiembre]



7.1.2.4 Observaciones Jack Knife 2120-CV003-C01 Trimestre 2 v/s Trimestre 3

Empeoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF33] Falla o ajuste de Guardera	Cuadrante **Agudo** a cuadrante **Agudo & Crónico**	MTTR 4,55 → 1,83 [hr] ↓ Frecuencia 01 → 07 [-] ↑	Tiempo 4,55 → 12,80 [hr] ↑	El MF33 pasa de cuadrante Agudo a cuadrante Agudo & Crónico con una disminución en el MTTR, pero aumento en su frecuencia. Aumento el tiempo indisponible.
[MF11] Daño en cinta transportadora	Se mantiene en cuadrante **Agudo**	MTTR 0,93 → 4,14 [hr] ↑ Frecuencia 01 → 02 [-] ↑	Tiempo 0,93 → 8,29 [hr] ↑	El MF11 se mantiene en cuadrante Agudo con un aumento en el MTTR y aumento en su frecuencia. Aumento el tiempo indisponible.
[MF29] Falla freno aparcamiento carro móvil	Se mantiene en cuadrante **Agudo**	MTTR 1,68 → 3,59 [hr] ↑ Frecuencia 01 → 01 [-]	Tiempo 1,68 → 3,59 [hr] ↑	El MF29 se mantiene en cuadrante Agudo con un aumento en el MTTR, pero manteniendo su frecuencia. Aumento el tiempo indisponible.
[MF27] Falla estación de polines	Cuadrante **Bajo Control** a cuadrante **Agudo**	MTTR 0,47 → 3,31 [hr] ↑ Frecuencia 02 → 01 [-] ↑	Tiempo 0,93 → 3,31 [hr] ↑	El MF27 pasa de cuadrante Bajo Control a Cuadrante Agudo con un aumento en el MTTR pero disminución en frecuencia. Genera un alto tiempo indisponible.
[MF40] Falla reductor	Aparece en cuadrante **Agudo & Crónico**	MTTR 3,26 [hr] Frecuencia 04 [-]	Tiempo 13,02 [hr]	El MF40 aparece en cuadrante Agudo & Crónico con alto MTTR y alta frecuencia. Genera un alto tiempo indisponible.
[MF38] Falla Polines	Aparece en cuadrante **Crónico**	MTTR 0,90 [hr] Frecuencia 04 [-]	Tiempo 3,61 [hr]	El MF38 aparece en cuadrante Crónico con bajo MTTR y alta frecuencia. Genera un alto tiempo indisponible.
[MF121] Otro mecánico (detención CM)	Aparece en cuadrante **Crónico**	MTTR 0,11 [hr] Frecuencia 12 [-]	Tiempo 1,28 [hr]	El MF121 aparece en cuadrante Crónico con bajo MTTR, por con alta frecuencia. El tiempo indisponible no es alto en comparación con los demás modos de falla pero genera problemas de confiabilidad en el equipo.

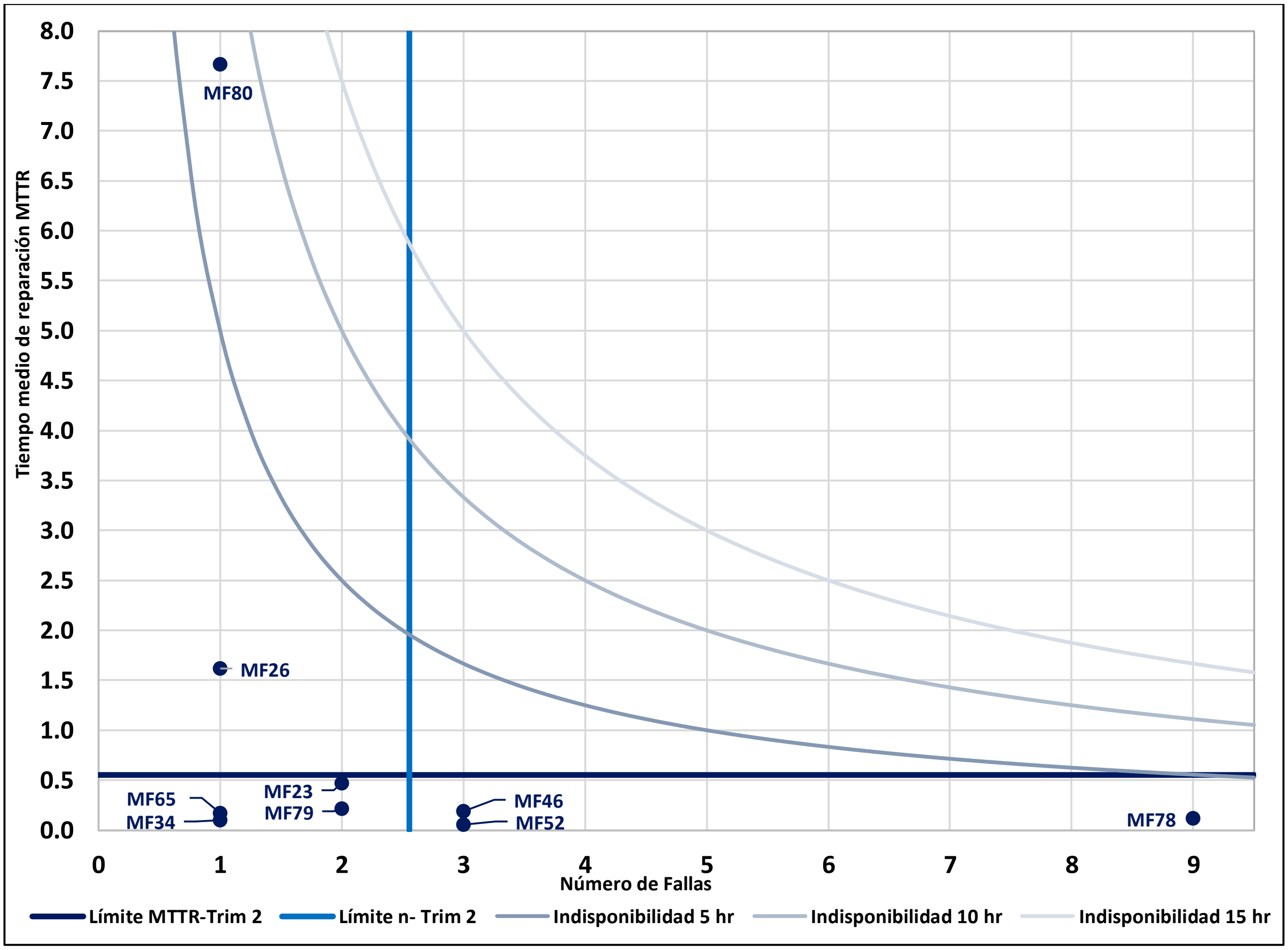
Mejoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF100] Falla de motor del motoreductor	Cuadrante **Agudo & Crónico** a cuadrante **Bajo Control**	MTTR 0,75 → 0,33 [hr] ↓ Frecuencia 04 → 02 [-] ↓	Tiempo 3,02 → 0,67 [hr] ↓	El MF100 pasa de cuadrante Agudo & Crónico a cuadrante Bajo Control con una disminución tanto en el MTTR como en la frecuencia. Este modo de falla se le aplicó un RCA.
MF[118] Otros instrumentación (sobre carrera)	Cuadrante **Crónico** a cuadrante **Bajo Control**	MTTR 0,13 → 0,28 [hr] ↑ Frecuencia 05 → 01 [-] ↓	Tiempo 0,64 → 0,28 [hr] ↓	El MF118 pasa de cuadrante Crónico a cuadrante Bajo Control con un aumento en el MTTR pero disminución en la frecuencia.
[MF56] Rotura/Fuga Chute	Desaparece de cuadrante **Agudo**	MTTR 2,86 [hr] Frecuencia 02 [-]	Tiempo 5,73 [hr]	El MF56 pasa de cuadrante Crónico a cuadrante Bajo Control con una disminución de la frecuencia pero aumento en su MTTR. Este modo de falla se controló mediante un ingeniero de desgaste.
[MF101] Falla de motor eléctrico	Desaparece de cuadrante **Crónico**	MTTR 0,32 [hr] Frecuencia 05 [-]	Tiempo 1,60 [hr]	El MF101 desaparece desde cuadrante Agudo & Crónico.
[MF66] Falla Del sensor de posición del carro móvil	Desaparece de cuadrante **Crónico**	MTTR 0,13 [hr] Frecuencia 03 [-]	Tiempo 0,38 [hr]	El MF66 desaparece desde cuadrante Agudo & Crónico.
[MF32] Falla frenos electromagnético del motoreductor (MEC)	Desaparece de cuadrante **Crónico**	MTTR 0,09 [hr] Frecuencia 03 [-]	Tiempo 0,28 [hr]	El MF32 desaparece desde cuadrante Crónico.

7.1.3 Análisis 3130-AD01-C02

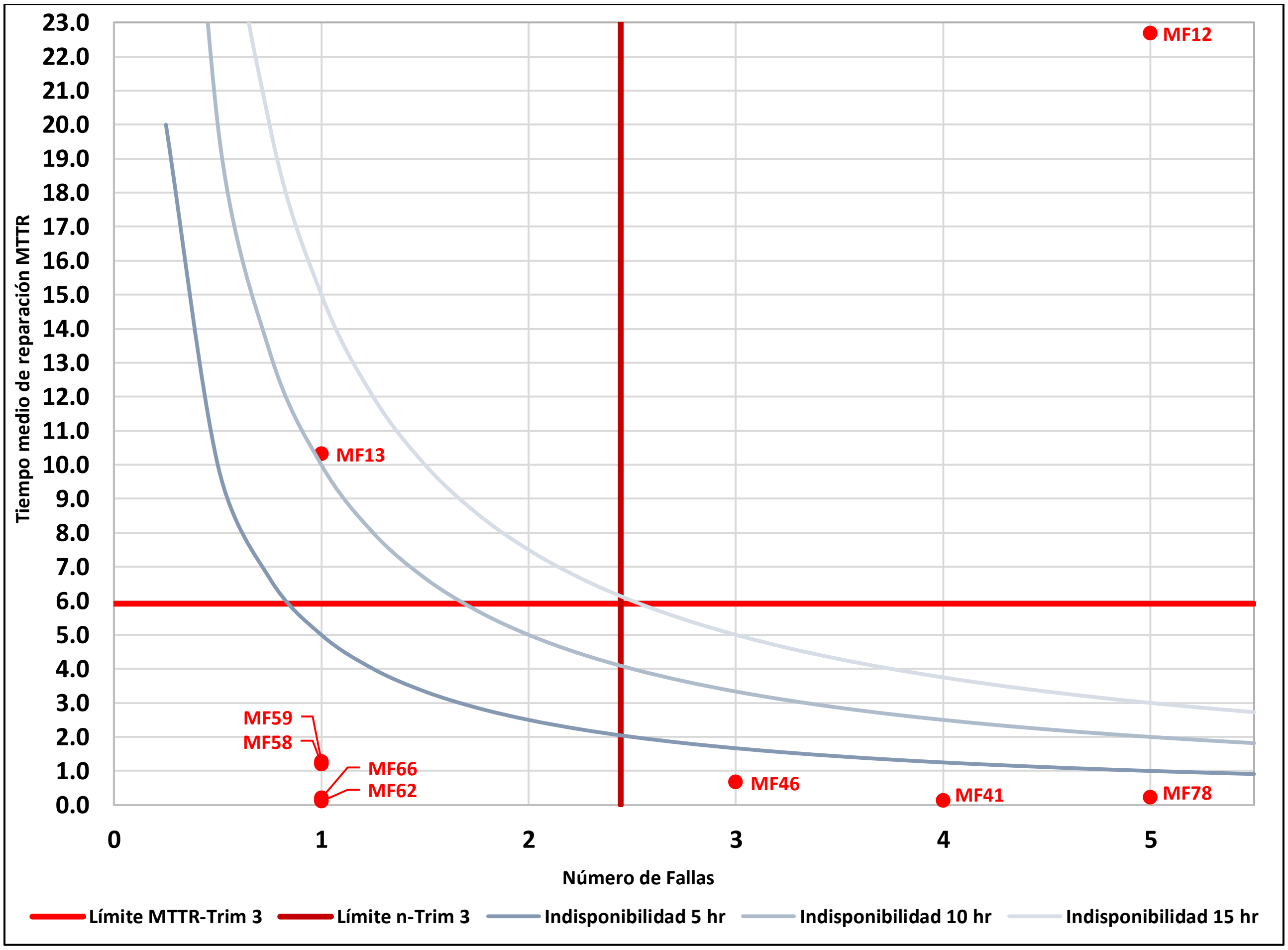
7.1.3.1 Jack Knife 3130-AD01-C02 Trimestre 2 [Abril-Mayo-Junio]

Modo de Falla	Modos de Falla (MF)	N° MF	n	MTTR	Dur
Fallas Agudas&Crónicas					
Fallas Crónicas					
Falla compresor	**3130-AD01-C02-MF78**	**MF78**	9	0,12	1,05
Sistema de lubricación de reductor	**3130-AD01-C02-MF46**	**MF46**	3	0,19	0,57
Falla de Variador de Frecuencia	**3130-AD01-C02-MF52**	**MF52**	3	0,06	0,17
Fallas Agudas					
Reparación línea de ácido	**3130-AD01-C02-MF80**	**MF80**	1	7,67	7,67
Falla de sistema suministro de acido	**3130-AD01-C02-MF26**	**MF26**	1	1,62	1,62
Fallas Bajo Control					
Falla Bomba Sistema Lubricación	**3130-AD01-C02-MF23**	**MF23**	2	0,47	0,93
Pruebas equipo	**3130-AD01-C02-MF79**	**MF79**	2	0,22	0,43
Otro Instrumentación	**3130-AD01-C02-MF65**	**MF65**	1	0,17	0,17
Falla Sistema Lubricación Piñón Corona	**3130-AD01-C02-MF34**	**MF34**	1	0,10	0,10

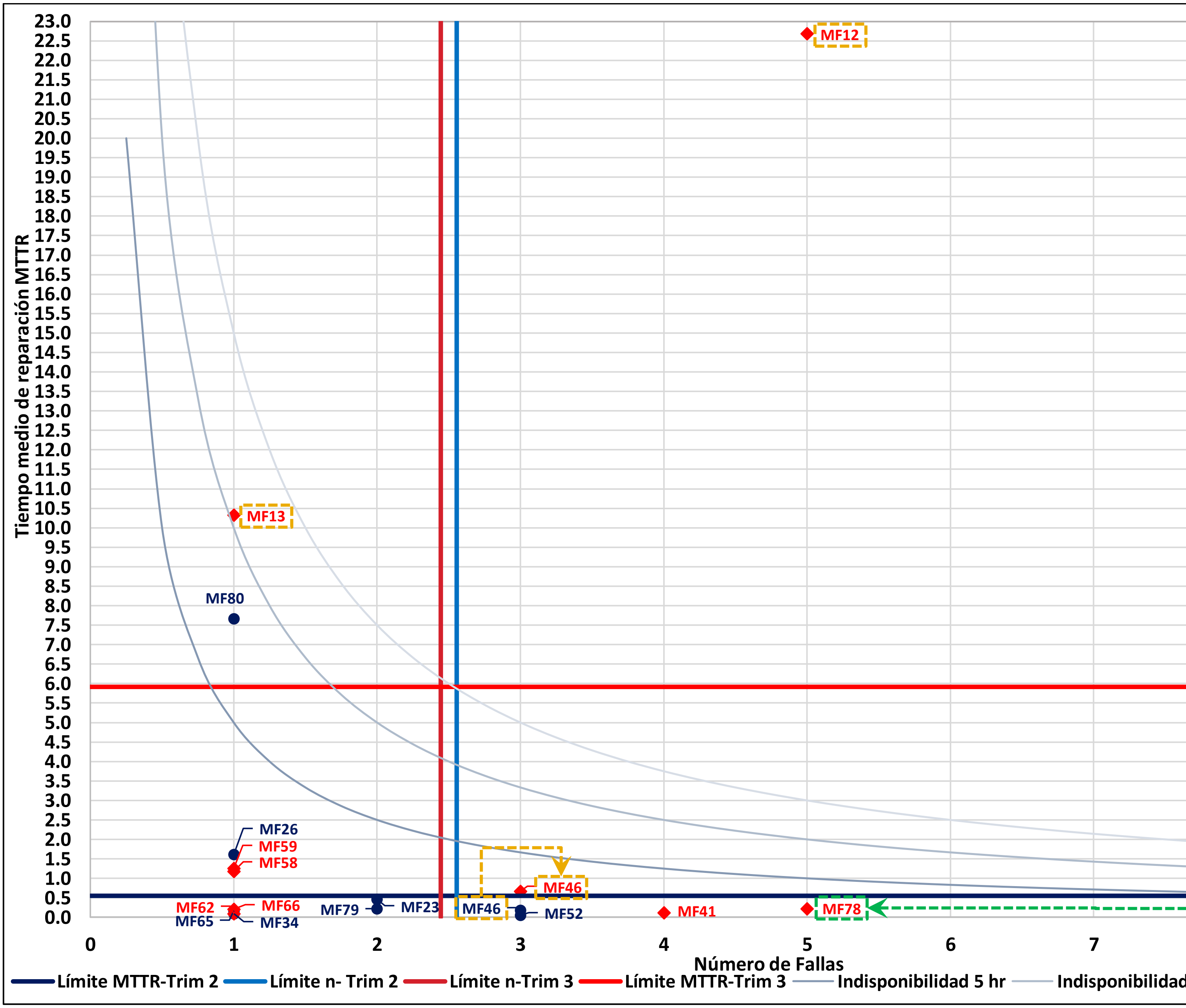


7.1.3.2 Jack Knife 3130-AD01-C02 Trimestre 3 [Julio-Agosto-Septiembre]

Modo de Falla	Modos de Falla (MF)	N° MF	n	MTTR	Dur.
Fallas Agudas&Crónicas					
Daño de revestimiento interior del Tambor	3130-AD01-C02-MF12	MF12	5	22,69	113,46
Fallas Crónicas					
Sistema de lubricación de reductor	3130-AD01-C02-MF46	MF46	3	0,67	2,01
Falla compresor	3130-AD01-C02-MF78	MF78	5	0,22	1,09
Inspección de Revestimientos	3130-AD01-C02-MF41	MF41	4	0,12	0,49
Fallas Agudas					
Daño estructural (MEC)	3130-AD01-C02-MF13	MF13	1	10,33	10,33
Fallas Bajo Control					
Falla sistema de control engrase Piñón/Corona	3130-AD01-C02-MF59	MF59	1	1,26	1,26
Falla Sensor Atollo	3130-AD01-C02-MF58	MF58	1	1,19	1,19
Corte de Energía	3130-AD01-C02-MF66	MF66	1	0,21	0,21
Falsa indicación	3130-AD01-C02-MF62	MF62	1	0,10	0,10



7.1.3.3 Jack Knife 3130-AD01-C02 Trimestre 2 [Abril-Mayo-Junio] v/s Trimestre 3 [Julio-Agosto-Septiembre]



7.1.3.4 Observaciones Jack Knife 3130-AD01-C02 Trimestre 2 v/s Trimestre 3

Empeoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF12] Daño de revestimiento interior del tambor	Aparece en cuadrante **Agudo & Crónico**	MTTR 22,69 [hr] Frecuencia 05 [-]	Tiempo 113,46 [hr]	El MF12 aparece en cuadrante Agudo & Crónico con alto MTTR y alta frecuencia. Genera un alto tiempo indisponible.
[MF46] Sistema de lubricación de reductor	Se mantiene en cuadrante **Crónico**	MTTR 0,19 → 0,67 [hr] ↑ Frecuencia 03 → 03 [-]	Tiempo 0,57 → 2,01 [hr] ↑	El MF46 se mantiene en cuadrante Crónico con un aumento en el MTTR, pero manteniendo su frecuencia. Aumento el tiempo indisponible.
[MF13] Daño estructural (MEC)	Aparece en cuadrante **Agudo**	MTTR 10,33 [hr] Frecuencia 01 [-]	Tiempo 10,33 [hr]	El MF13 aparece en cuadrante Agudo con alto MTTR y baja frecuencia. Genera un alto tiempo indisponible.

Mejoramiento de Modos de Falla [-]

Modo de Falla	Movimiento de Cuadrante	MTTR y Frecuencia	Tiempo Indisponible	Comentarios
[MF78] Falla compresor	Se mantiene en cuadrante **Crónico**	MTTR 0,12 → 0,22 [hr] ↑ Frecuencia 09 → 05 [-] ↓	Tiempo 1,05 → 1,09 [hr] ↑	El MF78 pasa se mantiene en cuadrante Crónico con un aumento en el MTTR pero disminución en la frecuencia. Aumenta levemente su tiempo indisponible.

7.2 Análisis GAMM Equipos

7.2.1 Análisis CV007

7.2.1.1 Gráfico GAMM 2220-CV007-C01 Trimestre 2 [Abril-Mayo-Junio]

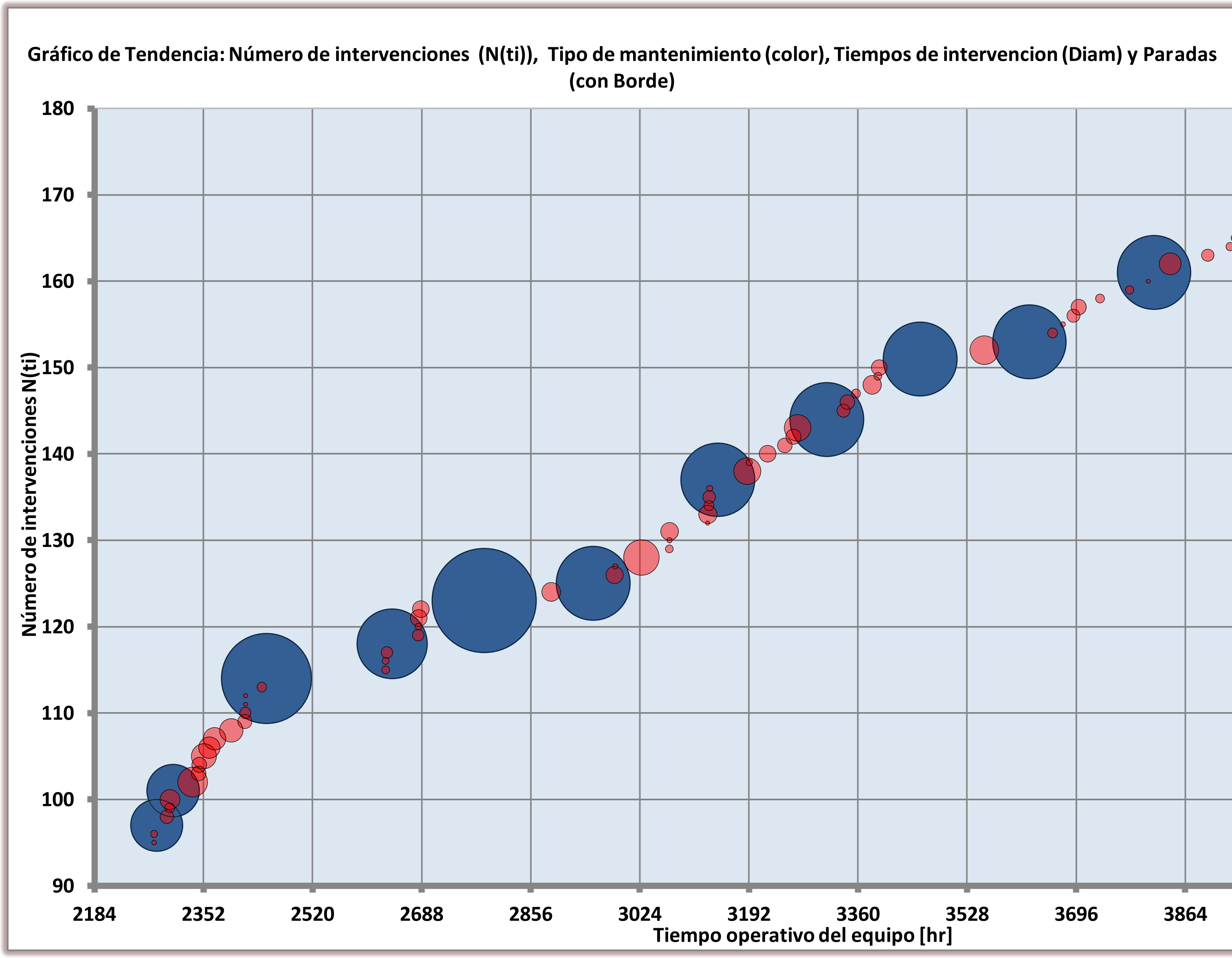


Gráfico de Tendencia: Número de intervenciones (N(ti)), Tipo de mantenimiento (color), Tiempos de intervencion (Diam) y Paradas (con Borde)

7.2.1.2 Análisis GAMM 2220-CV007-C01 Trimestre 2 [Abril-Mayo-Junio]

Tendencia en el comportamiento de las intervenciones

La gráfica muestra una tendencia lineal a lo largo del trimestre.

Desviación del mantenimiento preventivo

Se observa que el equipo presenta mantenciones preventivas en patrones cambiantes en un inicio para luego establecer un intervalo constante. Iniciando con mantenciones de 12 horas para luego pasar a mantenciones de 36 horas y finalmente intervenciones de 24 horas. .

Calidad de operación y/o mantenimiento preventivo

Se observan acumulación de mantenciones correctivas inmediatamente después de mantenciones preventivas (hasta 5 [hr] post MP). Lo anterior ocurre en 6 de las 14 mantenciones preventivas del trimestre. El MTTF post MP es de 27,23 [hr] y MTTR de 1,5 [hr]. En promedio hay 4,8 fallas entre mantenciones preventivas del equipo. La base de datos presenta gran variabilidad de modos de fallas inmediatamente después de mantenciones preventivas, principalmente modos de fallas asociados a la cinta (daños y cortes) y sistema motriz (frenos, sobre corriente, falla motor)

Eficiencia y calidad en la realización de las intervenciones

Se presenta variabilidad en la duración de las intervenciones de mantenimiento preventivo, de acuerdo a plan. Sin embargo, la manera en que se registra la base de datos no permite un análisis correcto ya que cualquier extensión del mantenimiento preventivo es categorizada con el modo de falla “mantención sobre programado” de tipo correctivo, cargando el mismo tiempo asociado a todos los equipos de la planta, independiente de qué equipo tuvo injerencia o no en la extensión de la mantención preventiva. Como regla de este reporte se eliminaron de la base de datos los modos de falla “mantención sobre programada” para evitar sumas incorrectas del tiempo de mantención correctiva.

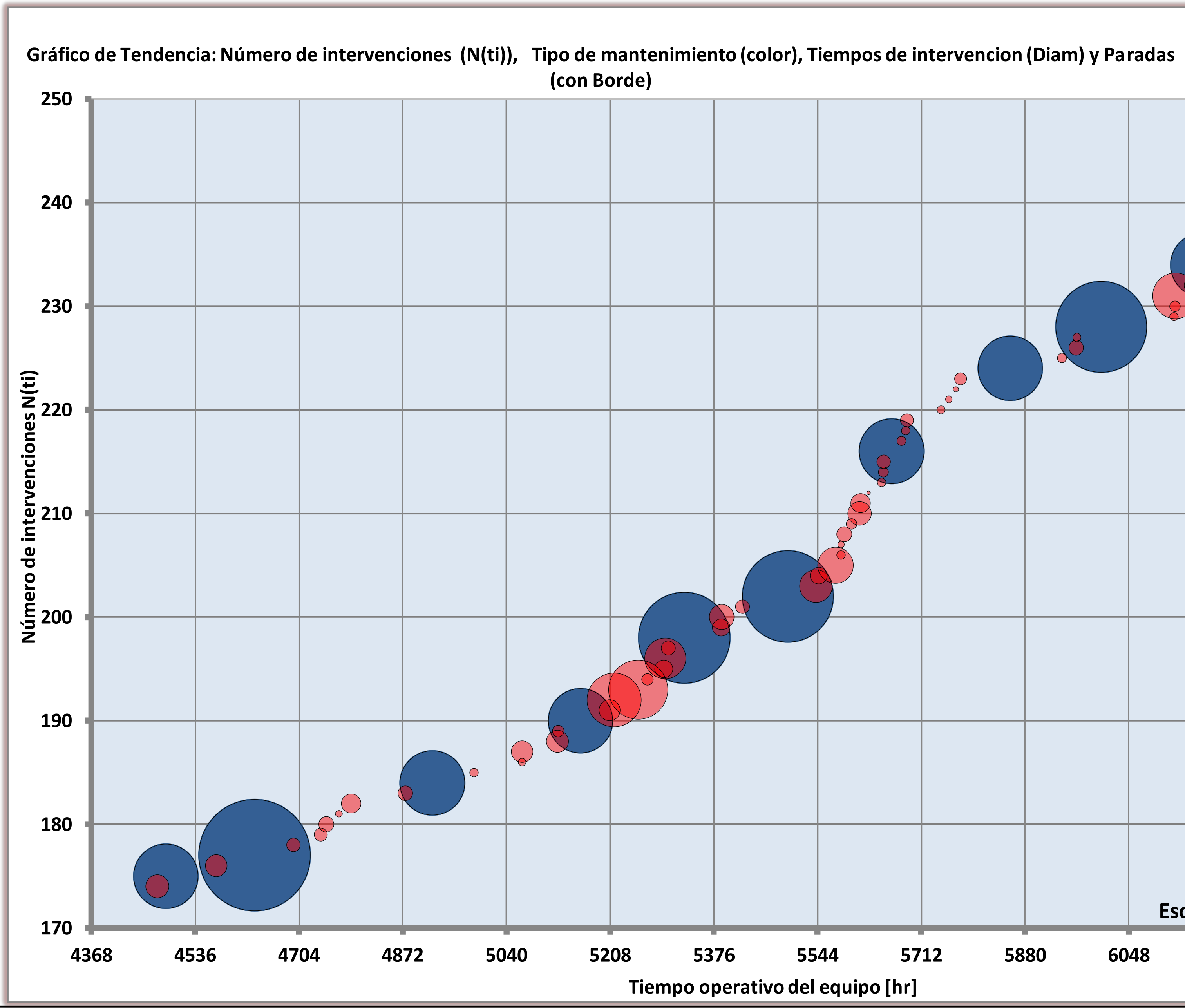
Por otro lado, las intervenciones de mantenimiento correctivo presentan un MTTR para el trimestre de 1,0 [hr], con desviación estándar de 1,073 [hr].

No se evidencia oportunismo en el mantenimiento preventivo, en relación a ocultar mantenciones correctivas de gran duración mediante el adelanto de mantenciones preventivas.

Observaciones generales:

El trimestre se evidencia problemas de confiabilidad asociados al carro móvil y daño en la cinta, en particular en el canto generado por la operación con Desalineamiento constante de la cinta.

7.2.1.3 Gráfico GAMM 2220-CV007-C01 Trimestre 3[Julio-Agosto-Septiembre]



7.2.1.4 Análisis GAMM 2220-CV007-C01 Trimestre 3 [Julio-Agosto-Septiembre]

Tendencia en el comportamiento de las intervenciones

La gráfica muestra una tendencia lineal a lo largo del trimestre.

Desviación del mantenimiento preventivo

Se observa que el equipo presenta mantenciones preventivas en patrones cambiantes. Iniciando con mantenciones de 12 y 36 horas para luego realizar de 24 horas y 12 horas.

Calidad de operación y/o mantenimiento preventivo

Se observan acumulación de mantenciones correctivas inmediatamente después de mantenciones preventivas (hasta 5 [hr] post MP). Lo anterior ocurre en 3 de las 12 mantenciones preventivas del trimestre. El MTTF post MP del trimestre es 41,79 [hr] y MTTR de 0,93 [hr]. En promedio hay 4,46 fallas entre mantenciones preventivas del equipo. La base de datos presenta variabilidad de modos de fallas inmediatamente después de mantenciones preventivas, principalmente modos de fallas asociados a la cinta (daños).

Eficiencia y calidad en la realización de las intervenciones

Se presenta una variabilidad en la duración de las intervenciones de mantenimiento preventivo, de acuerdo a plan. Sin embargo, la manera en que se registra la base de datos no permite un análisis correcto ya que cualquier extensión del mantenimiento preventivo es categorizada con el modo de falla “mantención sobre programado” de tipo correctivo, cargando el mismo tiempo asociado a todos los equipos de la planta, independiente de qué equipo tuvo injerencia o no en la extensión de la mantención preventiva. Como regla de este reporte se eliminaron de la base de datos los modos de falla “mantención sobre programada” para evitar sumas incorrectas del tiempo de mantención correctiva. Por ende, para evaluar este punto es necesario registrar una base de datos con extensiones de mantenimiento preventivo a consecuencia únicamente de la correa CV007.

Por otro lado, las intervenciones de mantenimiento correctivo presentan un MTTR para el trimestre 3 de 1,22 [hr] mayor al trimestre 2, con desviación estándar de 1,92 [hr].

No se evidencia oportunismo en el mantenimiento preventivo, en relación a ocultar mantenciones correctivas de gran duración mediante el adelanto de mantenciones preventivas.

Observaciones generales:

En conclusión, se observan cambios en la duración de las mantenciones preventivas pero manteniendo los intervalos entre ellas. Sin embargo, los cambios significaron una disminución leve del número de intervenciones correctivas.

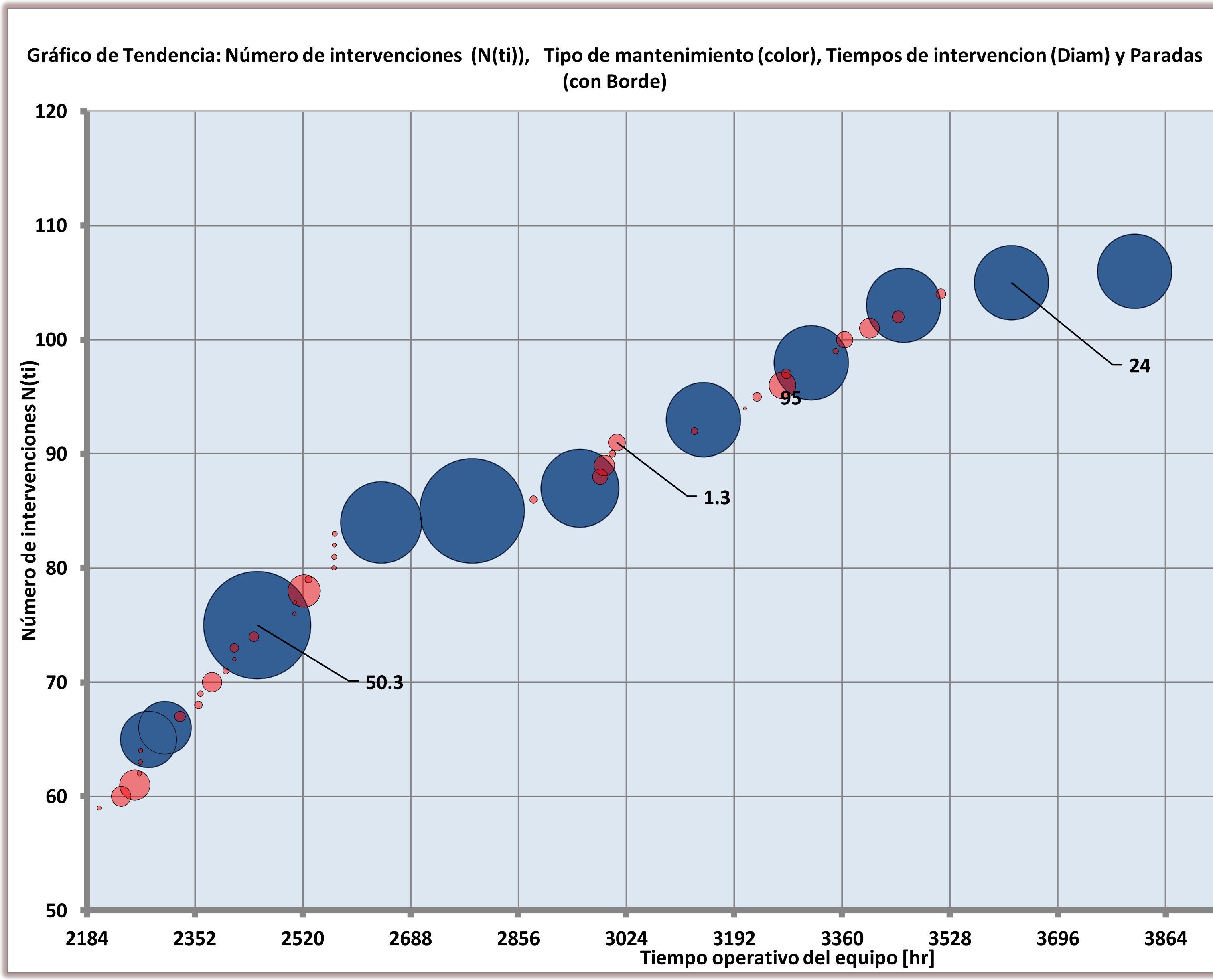
Se mantiene la cantidad de mantenciones correctivas inmediatamente después de mantenciones preventivas con respecto al trimestre anterior pero con mayor MTTF post MP.

Las detenciones asociadas al carro móvil disminuyen principalmente a los moto reductores pero aumentan las asociadas a la cinta transportadora. Por otro lado se evidencian fallas catastróficas asociadas al riel del carro móvil.

Se evidencia desaparición de las detenciones asociadas al raspador y acoplamiento hidráulico.

7.2.2 Análisis CV003

7.2.2.1 Gráfico GAMM 2120-CV003-C01 Trimestre 2 [Abril-Mayo-Junio]



7.2.2.2 Análisis GAMM 2120-CV003-C01 Trimestre 2 [Abril-Mayo-Junio]

Tendencia en el comportamiento de las intervenciones

La gráfica muestra una tendencia lineal a lo largo del trimestre.

Desviación del mantenimiento preventivo

Se observa que el equipo si presenta mantenciones preventivas en patrones constantes en el trimestre, con excepciones de aumentos de tiempos en dos intervenciones de acuerdo al plan anual. Existe cumplimiento de los intervalos de mantención preventiva a fecha constante con duración similar de intervención. Sin embargo, debido a la configuración del equipo en la planta y el registro de las intervenciones en la base de datos, el equipo se detiene al igual que toda la planta, por lo que la base de datos no discrimina si en realidad se realizaron actividades de mantenimiento preventivo durante la totalidad de las horas.

Calidad de operación y/o mantenimiento preventivo

No se observan acumulación de mantenciones correctivas inmediatamente después de mantenciones preventivas (hasta 5 [hr] post MP). El MTTF post PM es de 26,08 [hr] con un MTTR de 0,3 hrs, principalmente detenciones por comunicación y sobre corriente de motores. En promedio hay 5 fallas entre mantenciones preventivas del equipo.

Eficiencia y calidad en la realización de las intervenciones

El mantenimiento preventivo no presenta variaciones en la duración de la intervención a excepción de dos intervenciones que fueron programadas con mayor duración. Sin embargo, la manera en que se registra la base de datos no permite un análisis correcto ya que cualquier extensión del mantenimiento preventivo es categorizada con el modo de falla “mantención sobre programado” de tipo correctivo, cargando el mismo tiempo asociado a todos los equipos de la planta, independiente de qué equipo tuvo injerencia o no en la extensión de la mantención preventiva. Como regla de este reporte se eliminaron de la base de datos los modos de falla “mantención sobre programada” para evitar sumas incorrectas del tiempo de mantención correctiva.

Por otro lado, las intervenciones de mantenimiento correctivo presentan un MTTR para el trimestre 2 de 0,7 [hr], con desviación estándar de 1,03 [hr].

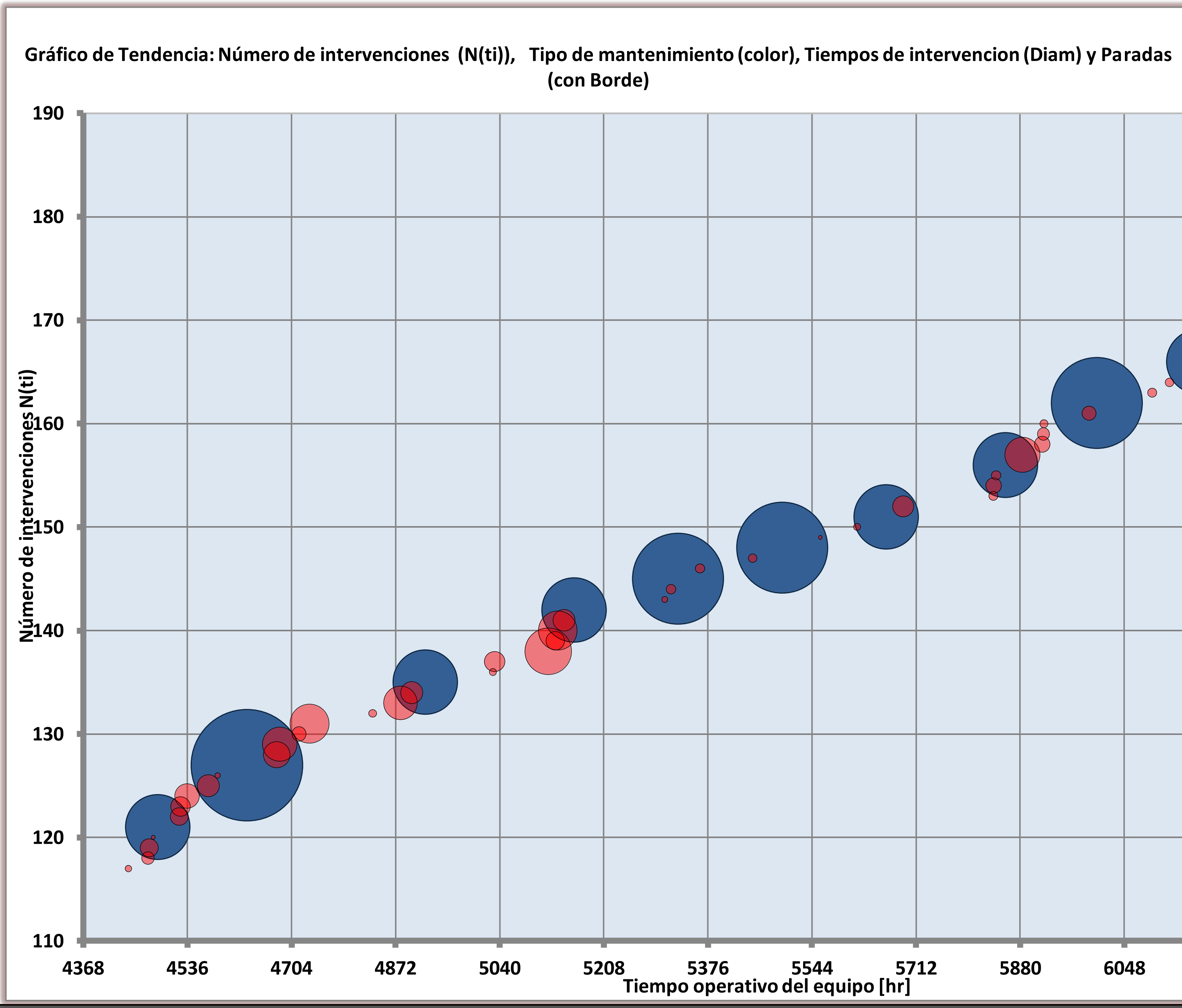
Las principales detenciones son asociadas al carro móvil, enfocadas en el sistema de localización y moto reductores.

No se evidencia oportunismo en el mantenimiento preventivo, en relación a ocultar mantenciones correctivas de gran duración mediante el adelanto de mantenciones preventivas.

Observaciones generales:

En conclusión, se evidencia problemas de confiabilidad debido a las detenciones asociadas al carro móvil y de roturas en chutes.

7.2.2.3 Gráfico GAMM 2120-CV003-C01 Trimestre 3 [Julio-Agosto-Septiembre]



7.2.2.4 Análisis GAMM 2120-CV003-C01 Trimestre 3 [Julio-Agosto-Septiembre]

Tendencia en el comportamiento de las intervenciones

La gráfica muestra una tendencia lineal a lo largo del trimestre.

Desviación del mantenimiento preventivo

Se observa que el equipo si presenta mantenciones preventivas en patrones constantes en el trimestre, con excepciones de aumentos de tiempos en dos intervenciones de acuerdo al plan anual. Existe cumplimiento de los intervalos de mantención preventiva a fecha constante con duración similar de intervención. Sin embargo, debido a la configuración del equipo en la planta y el registro de las intervenciones en la base de datos, el equipo se detiene al igual que toda la planta, por lo que la base de datos no discrimina si en realidad se realizaron actividades de mantenimiento preventivo durante la totalidad de las horas.

Calidad de operación y/o mantenimiento preventivo

No se observa acumulación de mantenciones correctivas inmediatamente posterior de mantenciones preventivas (hasta 5 [hr] post MP) a excepción de la última mantención preventiva. El MTTF post MP de 37,75 [hr] y MTTR de 1,4 [hr], principalmente detenciones de placas y Guarderas junto a una reparación extensa de la cinta por un daño. En promedio hay 4,11 fallas entre mantenciones preventivas del equipo.

Eficiencia y calidad en la realización de las intervenciones

El mantenimiento preventivo no presenta variaciones en la duración de la intervención a excepción de dos intervenciones que fueron programadas con mayor duración. Sin embargo, la manera en que se registra la base de datos no permite un análisis correcto ya que cualquier extensión del mantenimiento preventivo es categorizada con el modo de falla “mantención sobre programado” de tipo correctivo, cargando el mismo tiempo asociado a todos los equipos de la planta, independiente de qué equipo tuvo injerencia o no en la extensión de la mantención preventiva. Como regla de este reporte se eliminaron de la base de datos los modos de falla “mantención sobre programada” para evitar sumas incorrectas del tiempo de mantención correctiva.

Por otro lado, el MTTR de las intervenciones correctivas del trimestre fue de 1,0 [hr], con desviación estándar de 1,551 [hr].

Se evidencia una alta cantidad de detenciones de MTTR menor a 01 [hr] asociados a detenciones del carro móvil. Además, el trimestre presenta alta cantidad de detenciones asociadas a Guarderas y carro móvil.

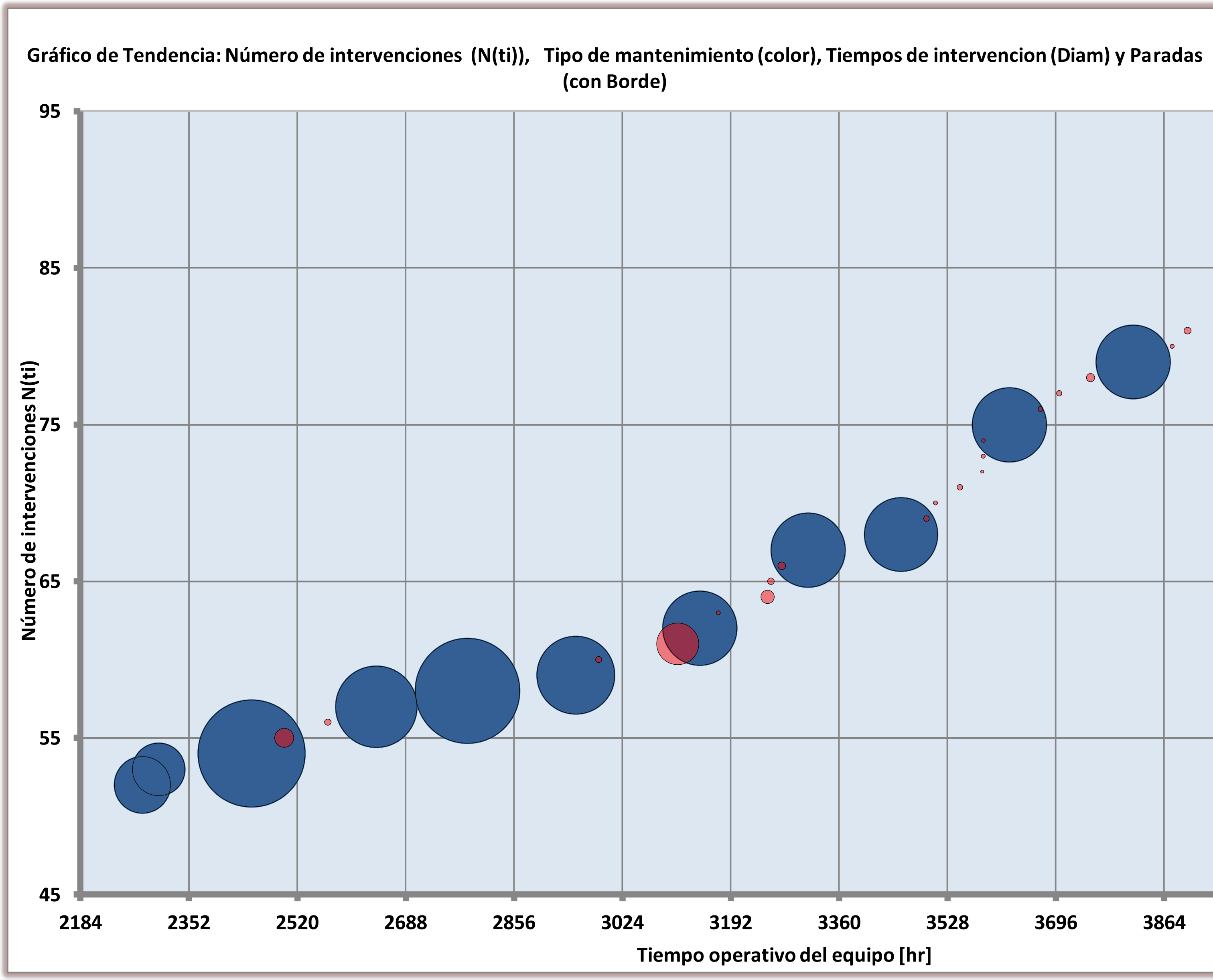
No se evidencia oportunismo en el mantenimiento preventivo, en relación a ocultar mantenciones correctivas de gran duración mediante el adelanto de mantenciones preventivas.

Observaciones generales:

En conclusión, se evidencia problemas de confiabilidad debido a las detenciones asociadas al carro móvil y de mantenibilidad en relación a la reparación de reductor.

7.2.3 Análisis AD01

7.2.3.1 Gráfico GAMM 3130-AD01-C02 Trimestre 2 [Abril-Mayo-Junio]



7.2.3.2 Análisis GAMM 3130-AD01-C02 Trimestre 2 [Abril-Mayo-Junio]

Tendencia en el comportamiento de las intervenciones

La gráfica muestra una tendencia lineal a lo largo del trimestre.

Desviación del mantenimiento preventivo

Se observa que el equipo si presenta mantenciones preventivas en patrones constantes en el trimestre, con excepciones de aumentos de tiempos en dos intervenciones de acuerdo al plan anual. Existe cumplimiento de los intervalos de mantención preventiva a fecha constante con duración similar de intervención. Sin embargo, debido a la configuración del equipo en la planta y el registro de las intervenciones en la base de datos, el equipo se detiene al igual que toda la planta, por lo que la base de datos no discrimina si en realidad se realizaron actividades de mantenimiento preventivo durante la totalidad de las horas

No se observan acumulación de mantenciones correctivas inmediatamente después de mantenciones preventivas (hasta 5 [hr] post MP). El MTTF post PM es de 26,08 [hr] con un MTTR de 0,3 hrs, principalmente detenciones por comunicación y sobre corriente de motores. En promedio hay 5 fallas entre mantenciones preventivas del equipo.

Calidad de operación y/o mantenimiento preventivo

No se observan acumulación de mantenciones correctivas inmediatamente después de mantenciones preventivas (hasta 5 [hr] post MP). El MTTF post PM es de 26,08 [hr] con un MTTR de 0,3 hrs, principalmente detenciones por comunicación y sobre corriente de motores. En promedio hay 5 fallas entre mantenciones preventivas del equipo.

Eficiencia y calidad en la realización de las intervenciones

El mantenimiento preventivo no presenta variaciones en la duración de la intervención a excepción de dos intervenciones que fueron programadas con mayor duración. Sin embargo, la manera en que se registra la base de datos no permite un análisis correcto ya que cualquier extensión del mantenimiento preventivo es categorizada con el modo de falla “mantención sobre programado” de tipo correctivo, cargando el mismo tiempo asociado a todos los equipos de la planta, independiente de qué equipo tuvo injerencia o no en la extensión de la mantención preventiva. Como regla de este reporte se eliminaron de la base de datos los modos de falla “mantención sobre programada” para evitar sumas incorrectas del tiempo de mantención correctiva.

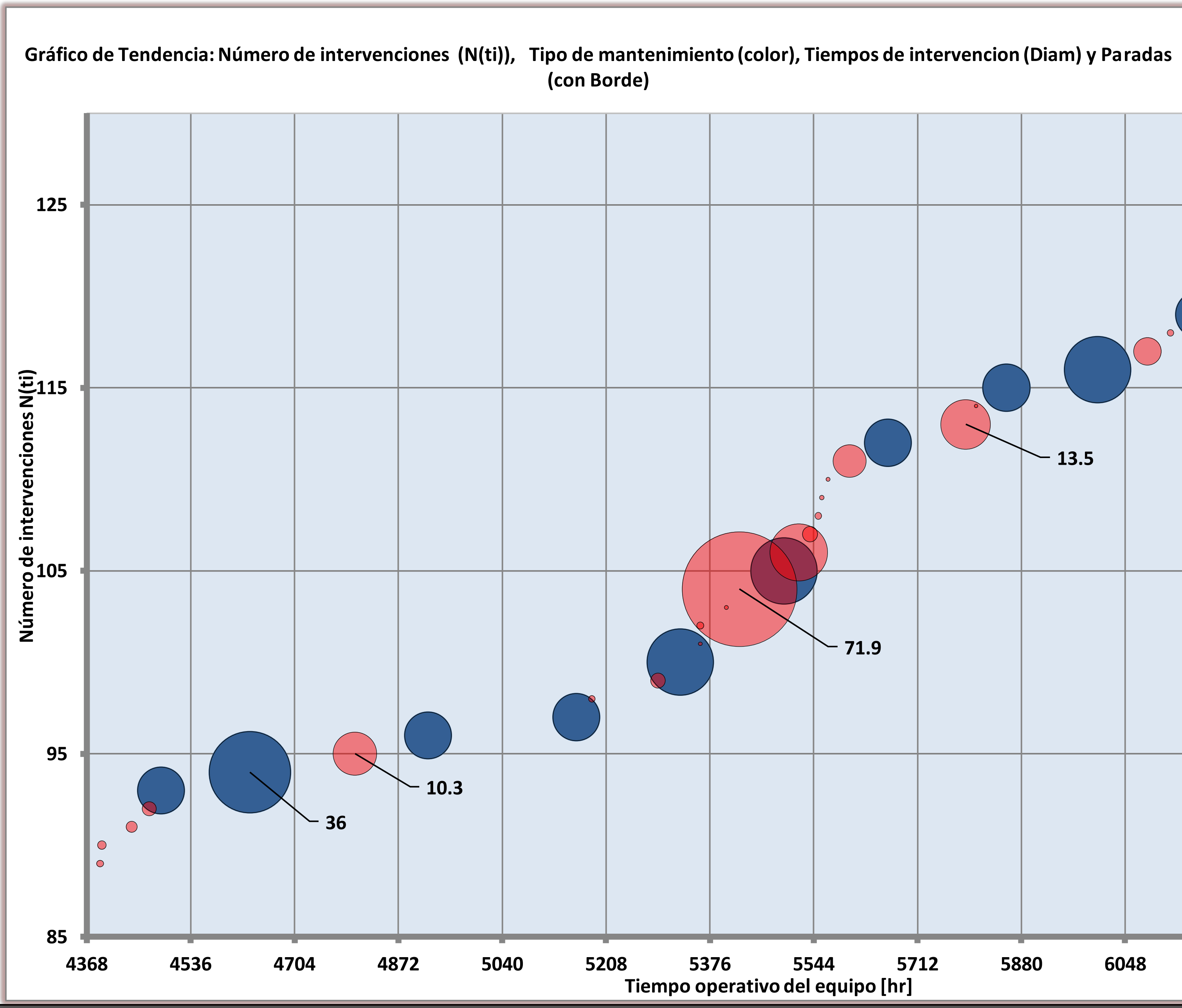
Por otro lado, el MTTR de las intervenciones correctivas del trimestre fue de 0,6 [hr], con desviación estándar de 1,58 [hr].

No se evidencia oportunismo en el mantenimiento preventivo, en relación a ocultar mantenciones correctivas de gran duración mediante el adelanto de mantenciones preventivas.

Observaciones generales:

En conclusión, se evidencia problemas de confiabilidad debido a las fallas de compresor y de mantenibilidad en relación a la reparación de línea de ácido.

7.2.3.3 Gráfico GAMM 3130-AD01-C02 Trimestre 3 [Julio-Agosto-Septiembre]



7.2.3.4 Análisis GAMM 3130-AD01-C02 Trimestre 3 [Julio-Agosto-Septiembre]

Tendencia en el comportamiento de las intervenciones

La gráfica muestra un periodo de concavidad para luego tener un comportamiento lineal

Desviación del mantenimiento preventivo

Se observa que el equipo si presenta mantenciones preventivas en patrones constantes en el trimestre, con excepciones de aumentos de tiempos en dos intervenciones de acuerdo al plan anual. Existe cumplimiento de los intervalos de mantención preventiva a fecha constante con duración similar de intervención. Sin embargo, debido a la configuración del equipo en la planta y el registro de las intervenciones en la base de datos, el equipo se detiene al igual que toda la planta, por lo que la base de datos no discrimina si en realidad se realizaron actividades de mantenimiento preventivo durante la totalidad de las horas.

Calidad de operación y/o mantenimiento preventivo

No se observan acumulación de mantenciones correctivas inmediatamente después de mantenciones preventivas (hasta 5 [hr] post MP). El MTTF post PM es de 52,46 [hr] con un MTTR de 6,6 hrs, principalmente detenciones por las reparaciones de revestimiento interior del tambor.

Eficiencia y calidad en la realización de las intervenciones

El mantenimiento preventivo no presenta variaciones en la duración de la intervención a excepción de dos intervenciones que fueron programadas con mayor duración. Sin embargo, la manera en que se registra la base de datos no permite un análisis correcto ya que cualquier extensión del mantenimiento preventivo es categorizada con el modo de falla “mantención sobre programado” de tipo correctivo, cargando el mismo tiempo asociado a todos los equipos de la planta, independiente de qué equipo tuvo injerencia o no en la extensión de la mantención preventiva. Como regla de este reporte se eliminaron de la base de datos los modos de falla “mantención sobre programada” para evitar sumas incorrectas del tiempo de mantención correctiva.

Por otro lado, el MTTR de las intervenciones correctivas del trimestre fue de 5,9 [hr], con desviación estándar de 15,55.

No se evidencia oportunismo en el mantenimiento preventivo, en relación a ocultar mantenciones correctivas de gran duración mediante el adelanto de mantenciones preventivas.

Observaciones generales:

En conclusión, se mantienen problemas con el compresor pero baja su frecuencia. Por otro lado, se presenta problema de mantenibilidad y calidad con respecto al revestimiento interior del tambor con alto MTTR y frecuencia. Lo anterior se expresa en el aumento del MTTR y desviación estándar del trimestre.

7.3 Seguimiento y Planes de Acción

Los modos de falla analizados a partir del Gráfico Jack Knife y luego revisados junto al equipo en el reporte GAMM, se presentan para seguimiento a partir de la planilla TOP-TEN.

7.3.1 Correa 2220-CV007-C01

Modo de Falla 11 – Daño en cinta transportadora

Plan de Acción Amenazas números: 6, 32 y 40. Completados en 100%.

Desalineamiento de la cinta	Ajuste de posición del sensor.	Mecánico	V. Soto / F. Acevedo	18-05-2016	100%	Se determina no cambiar la posición. Se debe trabajar en el alineamiento de la correa CV00
Daño de cinta	Generar solped de estado de cintas transportadoras. Diagnóstico especializado empresa Contitech.	Mecánico	R. Silva	19-05-2016	100%	
Cinta presentaba varios problemas	Mantención no programada: Retiro eje polín de estación centradora CV007, cortes de lonjas CV007 y ajuste bastón de desalineamiento 133A.	Mecánico	J. Cerda	21-05-2016	100%	

Modo de Falla 66 – Falla del sensor de posición del carro móvil

Plan de Acción Top Ten número: 9. Completado en 80%.

Falla inductivo del carro CV007	Evaluar activación de encoder u otro dispositivo existente como backup en el caso de humedad.	Instrumentación	F. Acevedo	10-11-2016	80%	12-07: Continúa en evaluación 20-07: Evaluación definió uso de GPS. En paralelo se realiza mejora de instalación de barredor. 26-07: Vendrá especialista de GPS para evaluación. (Se cambia fecha de cumplimiento) 02-08: Se define fecha de visita especialista para Jueves 11-08. 09-08: Se define fecha de visita especialista para Jueves 18-08. RFID pondrá redundancia a sensores inductivos (05/08 Septiembre) 30-08: Se coordina visita con Empresa RFID entre los días 05 y 08 de Septiembre. 06-09: 07 Septiembre viene la empresa 13-09: Empresa de GPS entregará informe de Factibilidad Técnica CV007.

Modo de Falla 83 – Falla sensor de velocidad cero

Sin plan de acción.

Modo de Falla 07 – Carro Fuera de Posición

Plan de Acción Amenazas números: 147, 148 y 149. Completados en 87%.

Descarrilamiento de carro móvil por falla rueda motor 7	Cambio de ruedas del carro CV007 por nuevo diseño reforzado.	Mecánico	J. Herrera	30-10-2016	100%	29-09: Se realizó el cambio de rueda y se debe realizar inspecciones a la rueda y vigas. Falta cambiar rueda motriz N° 3, 5, 8. 04-10: 05-10 se cambia la N°5. 12-10: se cambio rueda 8. Se quiebra eje de la rueda 8.
Descarrilamiento de carro móvil por falla rueda motor 7	Alineamiento de Rieles del carro CV007	Planificación	J. Cerda	30-10-2016	100%	29-09: Verificar con H. Cerda. 03-10: trabajo incluido en mantención mayor del 25-10
Descarrilamiento de carro móvil por falla rueda motor 7	Revisión y cambio de frecuencia de inspección de ruedas del carro CV007	Confiabilidad	B. Bugueño	15-10-2016	60%	13-09 : B. Bugueño modificará frecuencia en planilla de carga; R. Rosales lo subirá a SAP. 29-09: B. Bugueño continúa en modificación de frecuencia

Modo de Falla 79 – Falla sensor de límite de seguridad

Sin plan de acción.

7.3.2 Correa 2120-CV003-C01

Modo de Falla 33 – Falla o ajuste de Guardera

Plan de Acción Amenazas números: 100 y 128 Completados en 100%.

Falla o ajuste de guarderas y Falla Polines CV003 F/S por derrame de material cajón guía CV-003 por desprendimiento de gualdera L/D y lonja colgante.	Cambiar placas y guarderas en mantención programada	Mecánico	J. Herrera /J. Rivas	13-07-2016	100%	20-07: En mantención programada de 31-07 se agregará tramo pendiente. 26-07: Se ajustaron placas a 3mm en espera de placas modificadas. En plan de semana 31 se realizará cambio de 15 placas.
Placa guiadora de desgaste suelta (lado derecho sentido de carga) que fue instalada en mant. General planta					100%	

Plan de Acción Top Ten número: 12. Completado en 80%.

Falla o ajuste de guarderas	Revisión de frecuencia de cambio de guardera.	Planificación	B. Bugueño	20-10-2016	80%	26-07: Revisar y validar frecuencia (se reprograma) 27-09: incluir revisión de gualderas en frecuencia de inspección de placas. Se cambia plazo del15-08 para ingresar a plan mtto 01-11: Está incluido en la modificación de Pauta y Planes que deben ser subidos a SAP.

Modo de Falla 11 – Daño en cinta transportadora

Plan de Acción Amenazas número: 32. Completado en 100%.

Daño de cinta	Generar solped de estado de cintas transportadoras. Diagnóstico especializado empresa Contitech.	Mecánico	R. Silva	19-05-2016	100%	

Modo de Falla 29 – Falla freno aparcamiento carro móvil

Plan de Acción Amenazas número: 140 Completado en 60%.

Falla freno aparcamiento carro móvil Falla en unidad rail clamp carro CV003, nivel bajo aceite 2120-LAL-0031A	Incluir rail clamp en plan de mantención	Confiabilidad	B. Bugueño	15-10-2016	60%	27-09: Se envió planilla de pautas para subir al sistema SAP. R. Rosales debe cargar pautas y Planes que han sido modificados.

Modo de Falla 38 – Falla reductor

Plan de Acción Amenazas número: 113 y 114 Completado en 50%.

Falla reductor CV003	Reparación de reductor.	Planificación	J. Cerda	22-09-2016	0%	27-09: Averiguar status en maestranza que está reparando el reductor (SUMITOMO) 11-10: Esta semana se genera la OST y 3 semanas más para reparación, fecha final 04-11.
Falla reductor CV003	Revisar frecuencia de monitoreo	Sintomático	H. Cerda	18-08-2016	100%	13-09: Desde semana 31 se esta realizando monitoreo 2 veces por semana a sistema motriz, aumentando la frecuencia de inspección de 4 a 1 semana.

Modo de Falla 121 – Otro mecánico (detención CM)

Plan de Acción Amenazas número: 156 Completado en 50%

Detenciones CM CV003. Operadores informan que CM se detiene en reversa.	Evaluar la causa de la disminución de velocidad en el carro. No hay detención, se produce una baja de velocidad del carro sin existir una disminución de la referencia de velocidad.	Instrumentista Mecánico	S. Arredondo / P. Borquez	08-11-2016	50%	11-10: En mant de 12-10 se tratará de ubicar la causa del problema. 18-10: Una de las posibles causas, es que queden piedras en la cama de piedra actual del chute del carro, lo que genera frenado del carro. Este chute sera modificado por ing en la mtto mayor. hacer seguimiento de esta condición del carro posterior al cambio (revisar en la primera semana de noviembre). 08-11: Bajas las detenciones pero no se han presentado algunas detenciones. Se debe mantener en observación. Se solicitará a Ing DCS (R. Duran) las tendencias de partida y para en modo manual, con el objetivo de evaluar si sigue el evento.

Modo de Falla 27 – Falla estación de Polines

Plan de Acción Amenazas número: 50 y 83. Completado en 100%.

Fisura de estaciones de polines, en sector galería	Inspección y reparación de estaciones de polines	Planificación	R. Espinoza	31-05-2016	100%	14-06: solicitar información de la reparación que requiere la estación
CV003 Falla estación de polines. Retiro de 4 polines de estaciones de retorno dobladas	Cambio estación de polines en Mantención programada. En zona de descarga de cv001/2	Mecánico	J. Cerda	29-06-2016	100%	05-07: Se cambiaron en 29-06

7.3.3 Tambor Aglomerador 3130-AD001-C02

Modo de Falla 12 - Daño de revestimiento interior del tambor

Plan de Acción Amenazas números: 133, 142, 143, 144, 145 y 163. Completados en 100%.

Reparación de revestimiento roto del tambor	Generar OT de inspección diaria de revestimiento interior.	Planificación	J. Cerda	02-09-2016	100%	30-08: P. Borquez generará aviso para inspecciones diarias.
Desprendimiento de revestimiento del tambor aglomerado	Realizar RCA	Confiabilidad	R. Espinoza	08-09-2016	100%	
Desprendimiento de revestimiento del tambor aglomerado	Generación de procedimiento de limpieza de tambores	Operaciones	J. Latorre	20-09-2016	10%	13-09: En proceso.
Desprendimiento de revestimiento del tambor aglomerado	Generar Protocolo de inspección de revestimiento y lifter del tambor	Confiabilidad	R. Espinoza	15-10-2016	25%	
Desprendimiento de revestimiento del tambor aglomerado	Evaluar el cambio en tipo de revestimiento interior del tambor	Confiabilidad	R. Espinoza	30-11-2016	30%	Se esta evaluando con proveedores las alternativas de placa lifter. 18-10: se esta evaluando propuestas de DVA, Inrev, Rema Tip Top, Corrosion.
Tambor Aglomerado está perdiendo parte del revestimiento	Programar reparación mayor del revestimiento dañado, con vulcanizado en frio	Planificación	J. Cerda	30-10-2016	65%	04-10: Programado para la mantención mayor. 18-10: Cambiar fecha cumplimiento por cambio de mantención mayor. De 15-10 a 30-10. 01-11: En reparación mayor se avanzó con el cambio de revestimiento, pero aún quedan sectores por reparar.

Modo de Falla 46 – Sistema de lubricación de reductor

Sin plan de acción.

Modo de Falla 13 – Daño estructural (MEC)

Sin plan de acción. Vinculado a daño revestimiento interior.

Modo de Falla 78 – Falla compresor

Plan de Acción Amenazas número: 53, 54 y 98. Completados en 75%.

Falla sistema de engrasado (baja presión compresor)	Evaluar cambio de FLR del sistema de engrase.	Mecánico	J. Cerda	30-08-2016	100%	07-06: Se mandó a comprar dispositivos de engrase de tambor a FLR. 12-07 : J. Cerda evaluará un nuevo sistema. 20-07: Evaluar con empresa especialista (Farvel). Ricardo Rosales/ Ricardo Espinoza 26-07: Se ha cambiado el 50% de los FLR de los tambores. 06-09: Todos los FRL instalados.
Falla en compresor y baja presión en compresor	Cambiar cilindro actuador del dumper del compresor	Mecánico	J. Vildoso	08-06-2016	100%	El cilindro se instalará en mantención día 08-06
Falla de compresor principal	Instalar compresor standby.	Planificación	J. Cerda	10-09-2016	25%	05-07: Compresor se encuentra en faena para programar instalación. 12-07: Se solicitará JMIR evaluación de la instalación. 20-07: En espera de propuesta. R. Rosales 26-07: Ingersoll rand, evaluará compresor de 75 y propuesta se basa en sala eléctrica con todas las conexiones, Antucoya preparará la loza. En espera de propuesta. Pendiente evaluación de JMIR para loza. (se reprograma). 03-10: IR se adjudico la compra de un nuevo compresor con sala. Cambiar plazo de de cumplimiento del 10-09 a 15-11 por trabajos de instalación de la nueva sala

DOCUMENTACIÓN TESIS POR COMPENDIO

DOCTORADO EN INGENIERÍA MECÁNICA Y DE ORGANIZACIÓN INDUSTRIAL

Presenta:

Pablo Andrés Viveros Gunckel

Director:

Adolfo Crespo Márquez

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1. COPIA COMPLETA DE LAS PUBLICACIONES

ARTÍCULOS CIENTÍFICOS

1.1 Viveros Gunckel, P., Crespo Márquez, A., Barberá Martinez, L., and Gonzalez Rossel, J. P. (2016) Graphical Analysis for Operation Management: A Graphical Method to Support Operation Decision Making. Qual. Reliab. Engng. Int., 32: 2299–2311. DOI: 10.1002/qre.1936.

1.2 Viveros-Gunckel, P., Crespo-Marquez, A., Tapia, R., Kristjanpoller-Rodriguez, F., Gonzalez-Prida-Diaz, V. (2016). RELIABILITY STOCHASTIC MODELING FOR REPAIRABLE PHYSICAL ASSETS. CASE STUDY APPLIED TO THE CHILEAN MINING. DYNA, 91(4). 423-431. DOI: http://dx.doi.org/10.6036/7863

CAPÍTULO DE LIBRO

1.3 Gunckel, Pablo A. Viveros, Adolfo Crespo Márquez, Fredy A. Kristjanpoller, Rene W. Tapia and Vicente González-Prida. "Mathematical and Stochastic Models for Reliability in Repairable Industrial Physical Assets." Promoting Sustainable Practices through Energy Engineering and Asset Management. IGI Global, 2015. 287-310. Web. 16 Jan. 2017. DOI: 10.4018/978-1-4666-8222-1.ch012.

https://www.elsevier.com/__data/assets/excel_doc/0016/91123/Scopus_books_01_03_16.xlsx.

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Viveros-Gunckel, P., Crespo-Marquez, A., Tapia, R., Kristjanpoller-Rodriguez, F., Gonzalez-Prida-Diaz, V. (2016). RELIABILITY STOCHASTIC MODELING FOR REPAIRABLE PHYSICAL ASSETS. CASE STUDY APPLIED TO THE CHILEAN MINING. DYNA, 91(4). 423-431. DOI: http://dx.doi.org/10.6036/7863

Autor Principal: Pablo Viveros Gunckel

- Liderazgo en el desarrollo del artículo científico.
- Diseño conceptual de la propuesta de investigación.
- Investigación científica de los modelos estocásticos de confiabilidad para equipos reparables y No reparables.
- Prospección de empresas (Industra Minera) para aplicación de la propuesta.
- Validación de resultados con evidencia empírica.

Coautor 1: Adolfo Crespo Márquez

- Guía metodológica para el diseño y desarrollo del artículo científico.
- Revisión sistemática de los resultados en investigación científica y de la aplicación en la industria.

Coautor 2: René Tapia Peñaloza

- Soporte informático en la automatización de los modelos estocáticos, y construcción de herramienta prototipo.

Coautor 3: Fredy Kritjanpoller Rodriguez

- Levantamiento de datos en empresa minera para el caso aplicado.
- Validación de la data histórica para aplicación de los modelos por medio de reuniones de trabajo con el equipo supervisor de los activos.

Coautor 4: Vicente Gonzalez-Prida

- Revisión de los modelos estocásticos propuestos, y comparación con otras herramientas de soporte para la toma de desiciones en el área.
- Soporte en el estado del arte respecto a la utilización de los modelos estocásticos Reparables.

CONTRIBUCIÓN PARA CAPÍTULO DE LIBRO

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- Liderazgo en el desarrollo del capítulo del Libro.
- Diseño conceptual de la propuesta de investigación.
- Investigación de los modelos mátemáticos utlizados para representar activos con reparación perfecta e imperfecta.
- Validación del proceso GRP en activos industriales.

Coautor 1: Adolfo Crespo Márquez

- Guía metodológica para el desarrollo de capítulo de libro.
- Revisión de los modelos matemáticos aplicados en la propuesta.

Coautor 2: Fredy Kritjanpoller Rodriguez

- Soporte en la aplicación numérica del modelo de simulación GRP.

Coautor 3: René Tapia Peñaloza

- Automatización de los modelos matemáticos y estocáticos para facilitar la aplicación de éstos.

Coautor 4: Vicente Gonzalez-Prida

- Soporte en el diseño informático de un prototipo de alta escala
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Graphical Analysis for Operation Management: A Graphical Method to Support Operation Decision Making

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This paper proposes a graphical method to easy decision-making in industrial plants operations. The proposed tool 'Graphical Analysis for Operation Management (GAOM) method' allows to visualizing and analyzing production-related parameters, integrating assets/systems maintenance aspects. This integration is based on the Total Productive Maintenance model, using its quantitative management techniques for optimal decision-making in day-to-day operations. On the one hand, GAOM monitors possible production target deviations, and on the other, the tool illustrates different aspects to gain control on the production process, such as availability, repair time, cumulative production, or overall equipment effectiveness. Through appropriate information filtering, individual analysis by class of intervention (corrective maintenance, preventive maintenance, or operational intervention) and production level can be developed.

Graphical Analysis for Operation Management (GAOM) integrates maintenance information (number of intervention, type of intervention, required/not required stoppage) with production information (cumulative production, cumulative defective products, and cumulative production target) during a certain timeframe (cumulative calendar time, duration of intervention). Then the tool computes basic performance indicators supporting operational decision-making. GAOM provides interesting graphical outputs using scatter diagrams integrating indicators on the same graph. GAOM is inspired in the Graphical Analysis for Maintenance Management method, published by the authors (LB, AC, and PV) in 2012. Copyright © 2015 John Wiley & Sons, Ltd.

Keywords: Operation Management; Graphical Analysis; decision-making

1. Introduction

The industry has undergone significant changes over the past three decades, concerning management approaches, technologies, production processes, customer expectations, supplier management, and behavior of competition.[2] Because of the intense global competition, companies have worked to improve and optimize productivity in order to remain competitive. The need to improve productivity necessitated further integration of maintenance management to production management, with the ultimate goal of producing at minimum cost.

Efficiency management in production lines and manufacturing environments is gaining more importance, not only because it is a quality-neutral way to reduce production cost but also because of its role in ensuring the facility use with the best practices.[21] To achieve these goals, practical and easily implemented tools are needed allowing the identification of potential improvements in the production process are needed. Literature reviewed reveals that the industry still lacks approaches and tools to better understand the inefficiencies of machines,[19] particularly with a focus on production management decisions (quality, maintenance, and production planning).

Current business practice is characterized by intense international competition, rapid product innovation, increased use of automation, and significant organizational changes in response to new manufacturing and information technologies. Correspondingly, also the operating function is undergoing many significant changes using new technologically advanced equipment and new forms of organization.[20] The previous arguments suggest that the changes in the production environment are relevant for management control system.

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According to J. Fleischer,[3] the competitiveness of manufacturing firms mainly depends on variables such as the availability and productivity of their production equipment. The development and application of graphic tools that give support and make decisions in the field of operational reliability[15] is a fundamental task for the proper and efficient management of assets and resources within an organization, even more so with various types of equipment whose functional configuration is highly complex.[16,17] The emerging trend in current research is the integration of decision-making (DM) techniques in constructing an effective decision model to address practical and complex production problems.[18]

Typically, maintenance management has been analyzed independently to the management of production. This has hindered the comprehensive analysis of cause and effect between the two. It is therefore necessary to design tools and methods that facilitate the analysis and identification of losses in the production process, which allow giving answers to common questions in the area of production and maintenance (Table I). On the other hand, there is generally a lack of quality of information mainly due to collection processes and low operating complex data.[4,5] It is necessary procedures for the collection and management of simpler data and adjusted to real needs, facilitating the interpretation and analysis.[6,7,14] Here are some questions generally required by the area of production and maintenance, presented in an integrated way.

By definition, the performance measurement process corresponds to the quantification of the action, where the measurement is the quantization process and the action performance leads to Reference 8. Moreover, there is a relationship between the control and objectives formulation, setting standards, action programs, budgets, rational use of resources, measurement and verification of results, deviations, and performance correction or improvement.

Specifically, 26 DM techniques have been reviewed.[18] Nevertheless, the main revised methods taken into account to develop Graphical Analysis for Operation Management Method (GAOM) have been: Balanced Scorecard,[9,10] Total Productive Maintenance,[2–11] Overall Equipment Effectiveness,[12] and the Graphical Analysis for Maintenance Management (GAMM) method.[1]

2. Graphical Analysis for Operation Management Method

2.1. Introduction

The GAOM method is constructed from a database that integrates information from the production process through three classes of information: intervention (number of intervention, type of intervention, required/not required stoppage), production (cumulative production, cumulative defective products, and cumulative production target), and time (cumulative calendar time, duration of intervention).

Graphical Analysis for Operation Management Method (GAOM) integrates this information through the calculation of basic performance indicators related to timing information, production and quality, evaluating production yields and maintenance. To facilitate analysis, GAOM presents information graphically, using scatter diagrams, integrating performance indicators on the same graph. The software used by GAOM to calculate indicators and construct graphs, Microsoft Excel (VBA Language), has been widely used in companies of many sectors.

2.2. Input information

Input information is necessary for the success of the GAOM method. The classification for this input is presented in Table II.

Table I. Some important questions to be answered by the tool

Operations/production area

1. Which is the operating/running time between interventions, preventive intervention (PI) and corrective intervention (CI)?
2. Which is the non-operating time for operational intervention?
3. Which is the real production rate for equipment and overall system?
4. Which is the difference between ‘real production’ and ‘planned production’?
5. Which is the difference between ‘real production’ and ‘nominal production’?

Maintenance Area

1. Which is the frequency of corrective interventions between preventive interventions?
2. How variables are the ‘repair times’ for preventive interventions and corrective intervention?
3. How variables are the ‘functioning times’ after a preventive interventions and a corrective intervention?
4. Which is the effect of maintenance management decisions over performance indicators as intervention time and operation/running time?

Integrated Areas

1. Is there a deviation in equipment performance? Is it possible to identify the responsible area?
2. Are there accelerated wear patterns in the equipment?
3. Is the capacity of the plant adjusted to market demand?

Table II. Input information

Class	Description
a. Intervention information	
N° intervention (N_i)	Assigns the number of occurrence of the intervention *i*th. It is a natural number under consecutive order
Stop/do not stop (DET_i)	Reports whether the intervention stopped (0) or not stopped (1) the operation. It is a Binary variable.
Type of intervention (CI_i)	Corrective intervention (CM), associated with the value 1. It is a maintenance action after the occurrence of a failure. (CI_i=1) Preventive intervention (PM), associated with the value 2. It is a maintenance action prior to a failure. (CI_i=2) Operational intervention (OI), associated with the value 3. Do not execute a maintenance action. It generates a detention or reducing capacity performance. (CI_i=3)
b. Time information	
Cumulative calendar time (CCT_i)	It is the cumulative time when the *i*th intervention occurs. Counted from the beginning of the evaluation horizon (T=0).
Time of intervention (TI_i)	Time duration requested for the *i*th intervention. Related to the time to repair.
c. Production information	
Cumulative production (CP_i)	It is the cumulative production when the *i*th intervention occurs. Counted from the beginning of the evaluation horizon (T=0)
Cumulative defective production (CDP_i)	It is the cumulative defective production (out of quality standard) when the *i*th intervention occurs. Counted from the beginning of the evaluation horizon (T=0).
Nominal production capacity (NCP)	Nominal capacity of the process. It must be settled by operation.

It is necessary to emphasize that the measurement of throughput is taken at the output stage of the production process. Also, it works under the assumption that the actual production process does not exceed the settled nominal production capacity of it. First, is recommended to analyze a system from the overall point of view, identifying production deviations and the most important loss factors. Then, the equipment analysis will be interesting to determine the main causes of deviation or to refine the analysis. Figure 1 represents both possible analysis scenarios (equipment and system, respectively), showing, at the same time (red points) where measurement of the production input could be captured. This flexibility, understood as an advantage of GAOM, will be applied regarding users' interests and data availability.

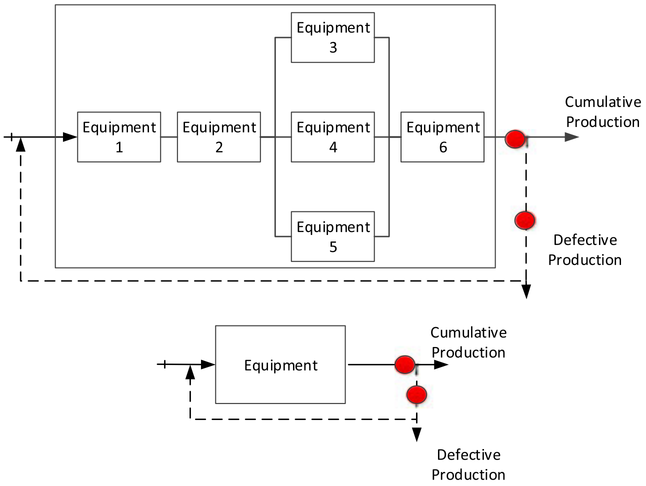


Figure 1. Analysis from process or equipment point of view.

2.3. Scatter diagram and basic performance indicators

To represent information in a clear and simple manner, GAOM uses a scatter diagram of cumulative production (CP_i) based on the cumulative number of interventions (N_i) for the *i*th intervention occurred along the time horizon.

The data presented in Table III refers to equipment used in a piping line, transporting inert material in a mining company located in Chile. Considering this, it is possible to generate the scatter diagram of the cumulative production (CP_i), based on the cumulative number of interventions (N_i) for the '*i*-esima' intervention (Figure 2). This diagram allows the analyst to evaluate the distribution and trend of cumulative production. (Tables IV and V)

According to the information related to 'input information' (Table II), it is recommended to collect the historical data considering the format shown in section 'Standard format for data collection' in Appendix A (Table VI).

From input information, GAOM requires to calculate some basic performance indicators, which are classified based on time or production (Tables IV and V).

Table III. Historical data of interventions and cumulative production (tons)

N_i	CP_i	N_i	CP_i	N_i	CP_i	N_i	CP_i	N_i	CP_i	N_i	CP_i
1	2165	10	20,192	19	47,243	28	66,217	37	76,751	46	81,002
2	3143	11	25,311	20	53,699	29	68,847	38	77,045	47	81,478
3	3777	12	27,989	21	54,792	30	70,279	39	77,301	48	81,963
4	7668	13	31,248	22	56,873	31	71,517	40	77,646	49	82,516
5	9972	14	32,024	23	57,894	32	72,452	41	78,241		
6	12,386	15	37,540	24	60,228	33	73,062	42	78,715		
7	15,965	16	41,590	25	61,817	34	74,375	43	79,238		
8	17,095	17	43,490	26	62,939	35	74,992	44	79,850		
9	17,992	18	45,236	27	64,174	36	76,264	45	80,457		

N_i, N° Intervention; CP_i, Cumulative Production.

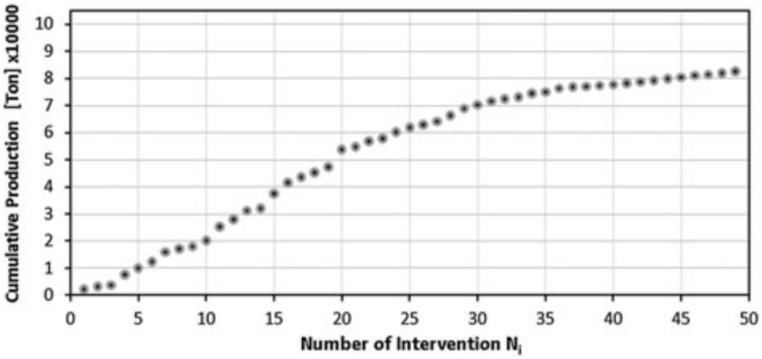


Figure 2. Scatter plot of cumulative production.

Table IV. BPI based on Time – GAOM method

N°	BPI	Description and formulation
1	Time between intervention (TBI_i)	Total time between intervention *i* and intervention $i-1$. $TBI_i = CCT_i - CCT_{i-1}$
2	Downtime of intervention (DT_i)	Time during the equipment does not operate. $DT_i = TI_i \times (1 - DET_i)$
3	Operating time (OT_i)	Time during the equipment is in operation. $OT_i = TBI_i - TI_{i-1} \times (1 - DET_{i-1})$
4	Cumulative operating time (COT_i)	Cumulated Operating time/working time when *i*th intervention occur. $COT_i = \Sigma\ OT_i$
5	Total cycle time (TCT_i)	This includes operation and intervention time. $TCT_i = TBI_i + DT_i$
6	Planned working time (PWT_i)	Time the organization has planned to operate. $PWT_i = TBI_i - DT_i$ (to preventive intervention) $TTP_i = TBI_i$ (to corrective or operational intervention)
7	Cumulated planned working time ($CPWT_i$)	Cumulative sum of planned working time. $CPWT_i = \Sigma\ PWT_i$

BPI, basic performance indicator; GAOM, Graphical Analysis for Operation Management.

Table V. BPI based on Production – GAOM method

N°	BPI	Description and formulation
1	Production between intervention (P_i)	Production processed during the time between interventions. $P_i = CP_i - CP_{i-1}$
2	Nominal cumulative production (NCP_i)	Cumulated production in chronological time (No intervention of any kind). $NCP_i = CCT_i \times NCP$
3	Cumulative planned production (CPP_i)	Production in the planned working time; that is, the planned production to nominal capacity, excluding the scheduled time of preventive interventions. $CPP_i = CPWT_i \times NCP$
4	Cumulative expected production (CEP_i)	Expected production during functioning time, i.e., the expected nominal production capacity, excluding the downtimes. $CEP_i = COT_i \times NCP$

BPI, basic performance indicator; GAOM, Graphical Analysis for Operation Management.

Table VI. Standard format

Intervention data			Production data		Time data	
Number of intervention	Class of intervention	Stop/no stop	Cumulative production	Cumulative defective production	Cumulative calendar time	Time of intervention
{0,1,2,…,N}	{1,2,3}	{0,1}	Productive unit	Productive unit	Time unit	Time unit
N_i	CI_i	DET_i	CP_i	CDP_i	CCT_i	TI_i
0	—	—	0	0	0	0
1	2	0	CP_1	CDP_1	CCT_1	TI_1
2	1	1	CP_2	CDP_2	CCT_2	TI_2
:	:	:	:	:	:	:
n	3	0	CP_n	CDP_n	CCT_n	TI_n

N_i, N° intervention; CP_i, cumulative production; TI_i, time of intervention; DET_i, stop/do not Stop; CI_i, type of intervention; CDP_i, cumulative defective production; CCT_i, cumulative calendar time.

To calculate the total cycle time TCT_i indicated in Table IV, there are four possible scenarios of detailed calculation shown in Figure 3. In this figure, the gray blocks represent interventions that produce equipment shutdown, while the white colored blocks represent interventions that do not require a shutdown of equipment.

2.4. *Analysis and graphs construction*

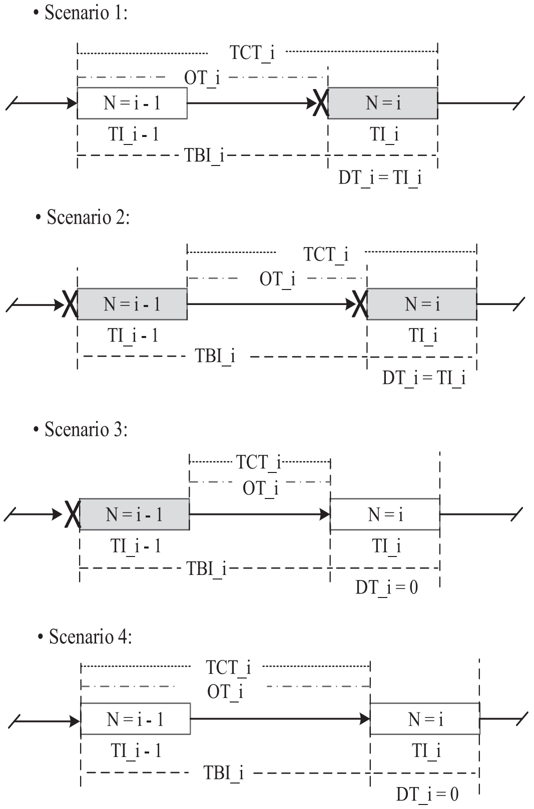
For subsequent analysis, GAOM requires to develop two new integrated databases, linking the previous data and basic indicators. For more details, see section 'Integrated databases' in Appendix B (Tables VII and VIII).

The GAOM method is constructed from a main production accumulated chart v/s number of intervention, this being a scatter diagram of bubbles (cumulative production) in which filters for the individual analysis of each type of intervention may be used, representing variables of interest including repair time or time between failures.

The bubble's dispersion function represents the cumulative production (CP_i)based on the accumulated number of intervention N_i for the *i*th intervention. The size (diameter) of the bubbles represent, relatively, the indicator results such as the time between intervention (TBI_i) shown in Figure 4, or the time of intervention (TI_i) shown in Figure 5 for the *i*th intervention. The bubble's color represents the type of intervention: dark gray (corrective maintenance), light gray (preventive maintenance), and white (operating procedure).

Graphical Analysis for Operation Management is capable of generating a total of eight graphics, namely:

- Graph 1: *Analysis of time between failures/interventions*. It displays the cumulative production in each intervention. Furthermore, the time between failures or interventions for each N_i is represented by the size of the bubble. This graph allows the analyzing of the effect of interventions on production. Furthermore, by comparing the size of the bubbles, it is possible to identify aging (systematic bubble size decrease) and the type of intervention phenomena, auditing the compliance of the established maintenance policy.
- Graph 2: *Analysis of intervention time*. It displays the cumulative production in each intervention. Furthermore, the repair time for each intervention N_i is represented by the size of the bubble. This new graphic complements the analysis in graph 1, discriminating whether the effect of loss production is cause of high frequency of failure (chronic failure phenomena) or long times repair. Furthermore, by comparing, the size of the bubbles can be detected labor behaviors related to a lack of discipline and/or work procedures for the development of interventions (high variability in the size of the bubbles), important differences



$DET_{i-1}=1$ y $DET_i=0$.
Intervention *i-1 does not stop the operation, while intervention i really does. OTi starts at the beginning of i-1 and finish at the beginning of i intervention. So, DT i=TI i, being TI i the duration of the intervention i.*

$DET_{i-1}=0$ y $DET_i=0$.
Interventions *i-1 and i stop the operation. OTi starts at the end of i-1 and finish at the beginning of i . So, DT i=TI i*

$DET_{i-1}=0$ y $DET_i=1$.
Intervention *i-1 stop the operation, while intervention i really does not. OTi starts at the end of i-1 and finish at the beginning of i. So, DT i= 0.*

$DET_{i-1}=0$ y $DET_i=1$.
Interventions *i-1 and i do not stop the operation. OTi starts at the beginning of i-1 and finish at the beginning of i . So, DT i= 0.*

Figure 3. Interventions timeline.

Table VII. Historical cumulative production data – GAOM

N_i	CP_i	TI_i	DET_i	OT_i	N_i	CP_i	TI_i	DET_i	OT_i
0	0	0	1	0	25	61,817	11	0	93
1	2165	6	0	132	26	62,939	18	0	58
2	3143	9	0	55	27	64,174	9	1	72
3	3777	6	0	32	28	66,217	12	0	126
4	7668	6	1	206	29	68,847	12	0	143
5	9972	16	0	127	30	70,279	8	0	80
6	12,386	6	1	127	31	71,517	7	0	72
7	15,965	6	0	192	32	72,452	7	1	64
8	17,095	13	0	62	33	73,062	9	0	36
9	17,992	7	0	47	34	74,375	21	0	77
10	20,192	8	0	116	35	74,992	7	0	33
11	25,311	8	1	280	36	76,264	7	0	79
12	27,989	8	0	147	37	76,751	9	1	35
13	31,248	8	0	169	38	77,045	9	0	19
14	32,024	16	0	41	39	77,301	8	0	17
15	37,540	9	0	288	40	77,646	9	0	19
16	41,590	9	1	217	41	78,241	17	0	33
17	43,490	15	0	117	42	78,715	7	0	27
18	45,236	9	0	93	43	79,238	9	1	29
19	47,243	9	0	105	44	79,850	10	0	41
20	53,699	10	1	325	45	80,457	7	0	35
21	54,792	17	0	70	46	81,002	9	0	32
22	56,873	10	0	117	47	81,478	10	0	32
23	57,894	10	0	58	48	81,963	7	0	33
24	60,228	10	0	128	49	82,516	10	0	32

N_i, N° intervention; CP_i, cumulative production; TI_i, time of intervention; DET_i, stop/do not Stop; OT_i, operating time; GAOM, Graphical Analysis for Operation Management.

Table VIII. Nominal, planned and expected cumulative production

N_i	PN_{Acum_i}	PP_{Acum_i}	PE_{Acum_i}	N_i	PN_{Acum_i}	PP_{Acum_i}	PE_{Acum_i}
1**	—	—	—	26	72,923	69,603	69,003
2*	7783	7583	7583	27*	74,723	71,043	70,443
3**	8603	8403	8263	28**	77,233	73,553	72,953
4**	12,833	12,433	12,293	29**	80,333	76,493	75,893
5	15,363	14,963	14,823	30*	82,163	78,163	77,563
6**	18,223	17,463	17,323	31**	83,753	79,753	78,993
7**	22,053	21,293	21,153	32**	85,163	81,023	80,263
8*	23,413	22,453	22,313	33*	85,883	81,743	80,983
9**	24,613	23,653	23,373	34	87,603	83,463	82,523
10**	27,073	25,933	25,653	35**	88,673	84,193	83,253
11**	32,823	31,483	31,203	36**	90,393	85,773	84,833
12**	35,763	34,423	34,143	37*	91,223	86,463	85,523
13**	39,293	37,753	37,473	38*	91,603	86,843	85,903
14	40,263	38,543	38,263	39**	91,923	87,163	86,043
15**	46,333	44,233	43,953	40*	92,263	87,343	86,223
16**	50,853	48,573	48,293	41	93,103	88,183	86,883
17*	51,993	49,713	49,433	42**	93,973	88,713	87,413
18**	54,153	51,873	51,433	43*	94,683	89,283	87,983
19**	56,423	53,963	53,523	44*	95,503	90,103	88,803
20**	63,343	60,703	60,263	45**	96,403	91,003	89,503
21*	63,693	61,053	60,613	46*	97,183	91,643	90,143
22**	66,373	63,733	63,133	47*	98,003	92,463	90,783
23**	67,733	64,913	64,313	48**	98,863	93,323	91,443
24**	70,493	67,513	66,913	49*	99,643	93,963	92,083
25**	72,543	69,383	68,783				

N_i, N° Intervention.

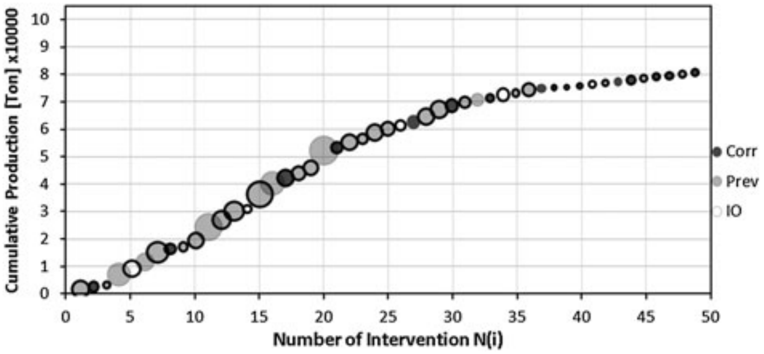


Figure 4. Graph 1: 'Analysis of time between failures/intervention'. Graphical Analysis for Operation Management method.

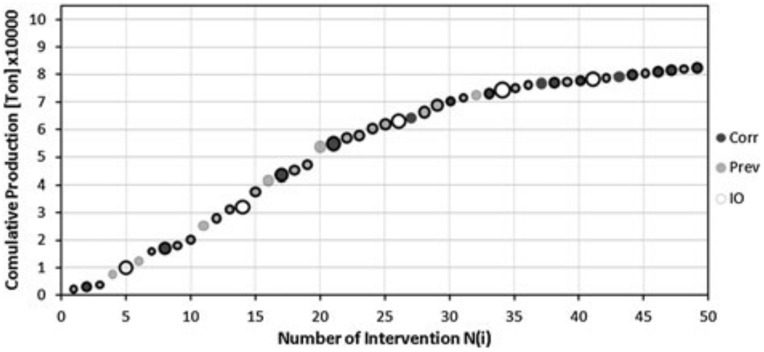


Figure 5. Graph 2: 'Analysis of intervention time'. Graphical Analysis for Operation Management method.

between the repair times linked to corrective or preventive interventions, atypical repair (size of bubble too big or too small), among others.

To perform an individual analysis of each type of intervention, GAOM is able to filter based on this variable. Thus, it is possible to analyze independently the behavior of each type of intervention, allowing the user to track variables patterns, analyzing and concluding about it. See graph 3.

- Graph 3: *Analysis of TBI, filtering corrective maintenance interventions*. This graph is equivalent to the structure presented in graph 1, except that only allows corrective maintenance analysis. This representation focuses the analysis on the phenomena of failure by detecting patterns such as representation in the package of interventions (scatter graph), often as cumulative production (differences in vertical axis), imperfect repair resulting in premature failures (size small bubbles), and aging, among others (Figure 6).
- Graph 4: *Analysis of TI, filtering preventive maintenance interventions*. This graphic is equivalent to graph 2 in structure, with the difference that allows analysis of preventive maintenance. This graph facilitates the analysis of planned maintenance and its effect on real output, considering: number of interventions, dispersion and frequency, times to repair's variability linked to maintainability (bubble size), among others (Figure 7).

The analysis of corrective maintenance interventions in a production process identifies the effectiveness of the maintenance policy. When equipment reaches a certain age, the failure rate starts to grow rapidly because of wear out.[13] To avoid this, it is necessary to optimize preventive maintenance, increasing, if any, the frequency of planned interventions. GAOM identifies the existence of an increasing failure rate (corrective maintenance) between preventive maintenance interventions. Figure 8 exemplified a production process where a policy of preventive maintenance is applied based on the amount of processed product, defined of course to prevent the occurrence of failures. It is seen as corrective maintenance interventions occur systematically and with similar amounts of processed product. This suggests that it is possible to identify the product processing factor generated by equipment failure, improving the policy of preventive maintenance and avoiding or reducing the occurrence of intermediate failures (dark-gray bubble).

- Graph 5: *Visualizing problems in the maintenance policy*. This graphic outlines the presence of a classical maintenance phenomenon: the incorrect definition of the frequency of preventive interventions. This phenomenon can be analyzed by an obvious pattern (Figure 8), as it is the permanent presence of corrective interventions from preventive interventions. This graph

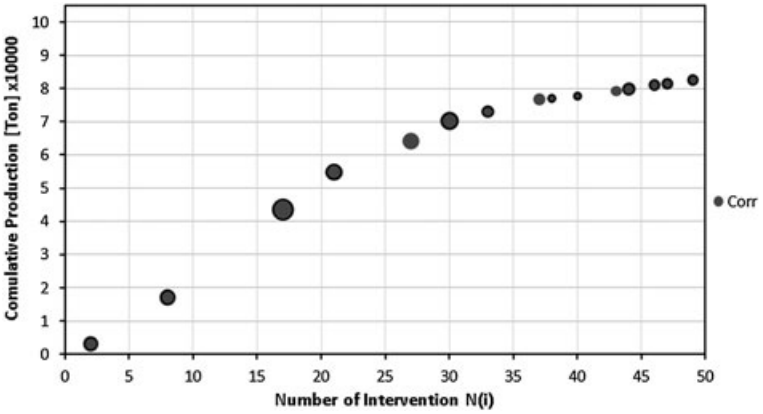


Figure 6. Graph 3: 'Analysis of time between failures filtering corrective maintenance interventions'. Graphical Analysis for Operation Management method.

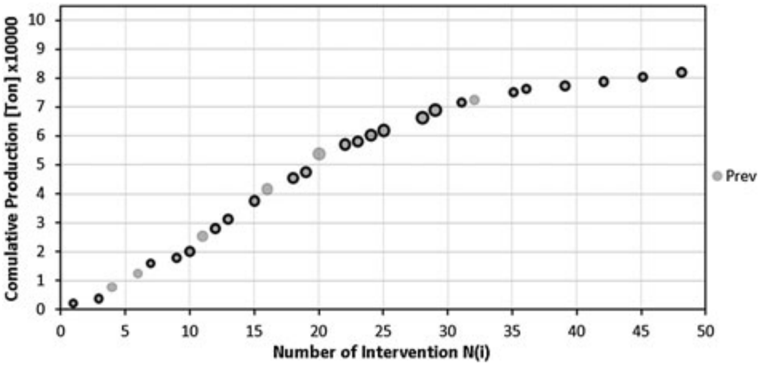


Figure 7. Graph 4: 'Analysis of time intervention filtering preventive maintenance interventions'. Graphical Analysis for Operation Management method.

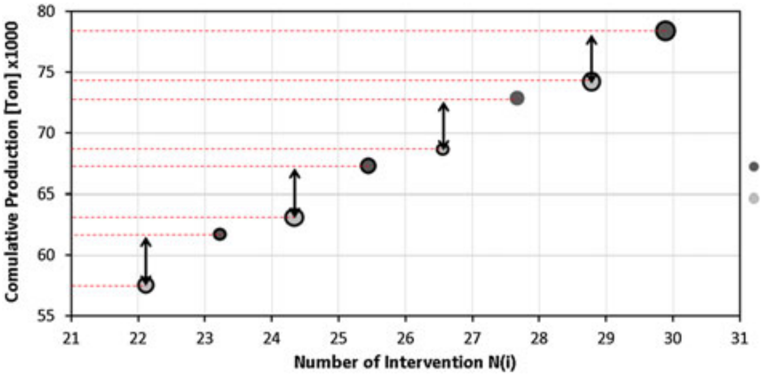


Figure 8. Graph 5: 'Display of problems in the maintenance policy'. Graphical Analysis for Operation Management method.

allows the preventive procedure to correlate with the level of cumulative production. The arrows drawn graphically explain and represent the production post preventive intervention, which is equivalent in time. There is clearly a correlation between production and maintenance, and it is clear too that corrective interventions are not considered to redefine the preventive frequency (scheduling).

Another use of filter type of intervention is the ability to manage operational interventions (white bubbles). This is possible by analyzing intervention times (linked to the repair time for operational response filter). GAOM is able to perform this type of analysis by displaying the bubble diameter as shown in Figure 9. Thus, GAOM allows us to focus on the analysis of those operational intervention longer stop operation, helping identify specific causes.[12]

- Graph 6: *Analysis of TI, filtering operational interventions*. This graphic is equivalent to graph 2 in structure, allowing only the analyzing of operational interventions. This graph allows you to focus on the presence of equipment operation phenomena, related to frequency and impact on production.

Meanwhile, losses of efficiency in processes generate deviations between actual and expected or planned production. It is necessary to control these deviations identifying the expected production target and the existing deviations. GAOM facilitates the analysis of these deviations, relating the nominal, planned, and expected production:

- Nominal/ideal production: production accumulated over time (ideal scenario without any kind of intervention) is given by the nominal process capability. Displays how the process should produce under Overall Effectiveness of the Asset with value 100%.[12]
- Planned production: corresponds to the expected production (at nominal capacity) during the work planned time. This time horizon does not include planned intervention as a possible time for production.
- Expected production: production quantity in the operating time, using the nominal capacity as the reference.
- Graph 7: *Analysis of TBI and production targets*. This chart shows the set of possible variables in a single graph. The dotted lines represent the nominal, planned, and expected production. Integrally, this chart allows us to analyze the impact of different phenomena intervention on production, compared with an ideal and/or planned scenario. For the latter, the analysis is complemented with graph 8.

It is also possible to identify any deviation between the actual cumulative production and expected cumulative production by analyzing the behavior of the vertical distances between the center of the respective bubbles and the curve of cumulative production target (Figure 11).

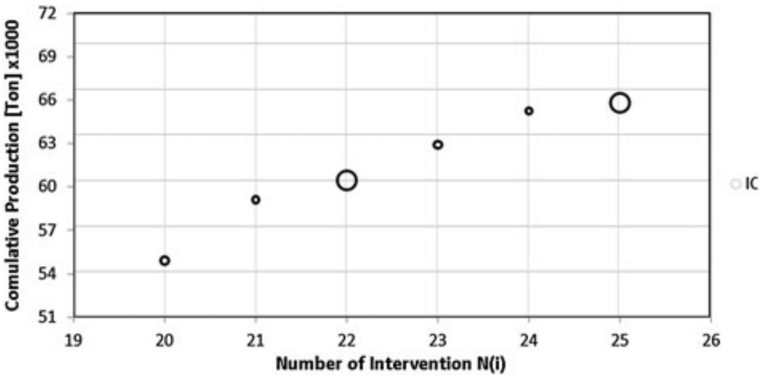


Figure 9. Graph 6: 'Analysis of time intervention with filter of operational interventions'. Graphical Analysis for Operation Management method.

- Graph 8: *Deviation between the actual cumulative production and cumulative production target*. This graph is an exemplification of a possible analysis from graph 7. Allows clearly the identification of any deviation to the production target, considering one or more interventions. The arrows drawn graphically explain and represent the difference of production between both curves at any *i*th intervention, clarifying some kind of patron between the type of intervention and the production delta. Also, it is possible to clarify some increase/decrease of production steadily over time.

Regarding the presented graphics, it is important to mention how it must be integrated in each particular analysis and graph into the GAOM proposal, identifying problems and phenomena to improve and/or research, reaching correct conclusions. For this, it is mandatory to follow some basic rules (3), particular recommendations (4), and the analysis and results in Section 3.

Basic rules:

- The procedure for GAOM proposal construction must follow this sequence: data source identification ensuring quantity and quality, relevant input filter, design and calculation of basic performance indicators, and finally, graphics construction and analysis.
- The procedure for GAOM analysis depends of the level of knowledge and particular interest of the analysts, then the starting point for inquiring could be:
  - Having already identified some particular phenomena (e.g., overload, accelerated wear, etc.) using graphs to explain and measure the effect, supporting key performance indicator's results.
  - General search for phenomena that have the effect on the breach of goals (low productivity, availability and/or utilization), then GAOM analysis will support, preliminary, to identify the cause of unproductivity.
- The graphics lecture and analysis must be always from a global (graphs 1, 2, and 7) to a particular (graphs 3, 4, 5, 6, and 8) point of view.

Recommendations:

- Multidisciplinary teamwork for graphs' interpretation.
- To identify trends we recommend using at least 3 months of historical data.
- To analyze phenomena affecting production, we recommend filtering in short periods, ideally every week.
- Integrate GAOM into the enterprise resource planning systems (ERP) (production and maintenance) and standardize sequence analysis.

3. Analysis and results

GAOM allows answering the questions initially posed in Table I:

- Area of operation/production answers

GAOM allows us to select between the basic performance indicators time between intervention/failures (TBI) and TI, making it possible to analyze trends and outliers over time between failures of computer data, as well as intervention times. Moreover, for the specific time display of operational interventions, GAOM allows filtering by type of intervention (Figures 6, 7, and 8), allowing work only with data type required intervention.

The production rate is shown by comparing the curves in Figure 10, which shows the relationship between the ideal scenarios, planned and expected, even if the center of each bubble (actual production) differs considerably from the rest of the dotted curves. This indicator is particularly important for analyzing equipment load.

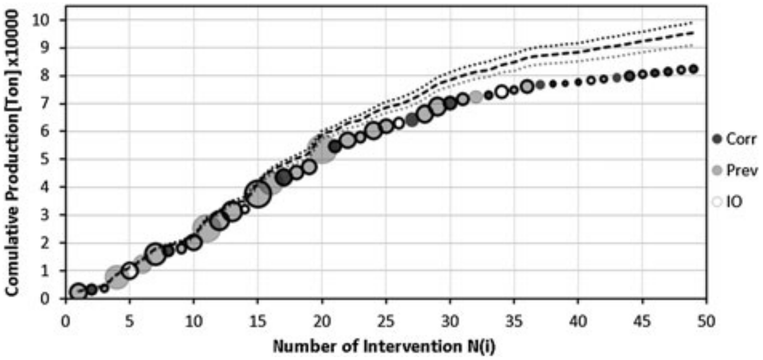


Figure 10. Graph 7: 'Analysis of time between intervention and production targets'. Graphical Analysis for Operation Management method.

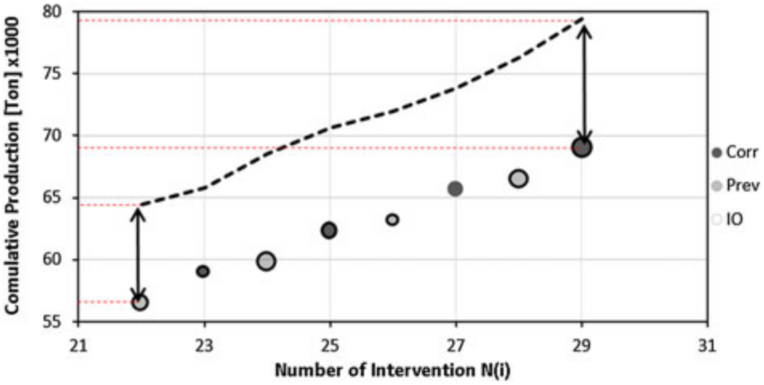


Figure 11. Graph 8: 'Deviation between the actual cumulative production and cumulative production target'. Graphical Analysis for Operation Management method.

It is possible to quantify the deviation between the actual output and production targets (planned and nominal) by analyzing the difference in the vertical axis (graph 8, Figure 11), either for current production status between one or various interventions or to analyze the effect that an intervention has had on the production system.

- Answers to maintenance area

The frequency of corrective interventions 'CM' between preventive interventions 'PM' can be show by graphic analysis of Figures 6 and 7, applying the filter of intervention that seeks to simplify the analysis for each type of maintenance. After applying the filter, a simple counting process is executed.

Using graph 2 (Figure 5) analysis of intervention time, applying preventive and corrective maintenance filters respectively, it is possible to analyze the behavior of the execution times of preventive maintenance and assess the adequacy of response from the maintenance area to corrective interventions, in terms of time is concerned. This is useful to improving the maintainability of the assets analyzed, for example, by a stock management, more efficient spare parts, investment in technology, design work areas, staff training, among others.

It is possible to analyze the evolution in time of the selected indicator using both filters, either in a first phase, time between failures or repair time (bubble diameter) and, secondly, the type of intervention to be analyzed.

- Answers to integration areas

It is possible to know if there is a shift in the equipment performance and identify the responsible area by vertical comparison between actual production (bubbles) and the dotted lines of the most ideal scenarios. Furthermore, by comparing the dotted lines (ideal scenario, planned and expected), the distance between them also provides information on possible causes of production losses. Two possible cases occur:

- Case 1: considerable distance between the actual curve (bubble center) and expected curve, indicating that the loss of production is due to a variation on the workload of the equipment or system.
- Case 2: considerable distance between expected and planned curve, indicating that the loss of production is mostly caused by unplanned events.

Common symptoms associated with the accelerated wear out of equipment can be identified by analyzing the evolution of changing times of good performance (tendency to decreased bubble radius, Figure 4) and partly by analyzing increases of intervention time (trend increasing bubble radius, Figure 5). Analyzing the accelerated wear out of the equipment allows identifying of potential investments for equipment replacement.

Analyzing the impact and trends of operational interventions (Figure 5) because of falls in demand can be estimated if the plant capacity is adequate. This information may be useful in evaluating possible decisions regarding plant capacity.

4. Conclusions

This paper presents the GAOM method, which integrates the main indicators of maintenance and production, mainly: cumulative production, intervention times (corrective maintenance, preventive and operational interventions) and time between failures/intervention. With GAOM it is possible to identify individual or systemic phenomenon, measuring, evaluating or auditing the impact of decision related to operational procedures or maintenance policies or strategies; as well as incorporating the tool as a 'big picture' of process performance, supporting to control operation and maintenance management. GAOM summarizes and complements the decision process to reduce production losses and thus maximizing business benefits.

The GAOM method consists of seven input information and one optional production data (production target). The information is classified as 'intervention' (number of intervention, type of intervention, and stopped/not stopped equipment), 'production' (cumulative production and defective products) and 'time' (calendar accumulated time and time intervention).

GAOM, through a preliminary analysis, manages to answer all original questions (Table I), demonstrating its effectiveness to support in a joint and independent manner, maintenance and production areas. For its construction, has sought an innovative design and easy to interpret, using graphics with high synergy in the information provided. It is complemented with simple indicators supporting making decisions. The integration between variables related to maintenance and operations impacting yields indicators for the overall management of the process.

GAOM supports analyst's measurement, computing and validating indicators. However, it should be noted the importance of quality and quantity of historical data. It is recommended the integration with other tools that center their analysis on complementary indicators, such as the $GAMM^2$ tool, focused maintenance management analysis. Thus, integration of both tools (GAMM Y GAOM) would integrate more information about operations management, production and maintenance. This would improve the optimization of maintenance policies.

Another important feature GAOM is its flexibility to control processes at the level of equipment or system. This feature can be used as a mechanism to search for opportunities for improvement, starting from an overview of the system for, afterwards, subsystems and equipment analysis.

Regarding applicability of this method, the design of the tool allows to process information of any production process. To process the information, common calculation tools can be used as VBA (Visual Basic Programming) programming spreadsheet, or generation of algorithms for processing graphs that are part of the tool. As future lines of research, there is great development potential of the tool on automation, using more advanced programming languages that enable its implementation in ERP, such as ERP SAP-PM. Another area of development is the application of GAOM in different production scenarios, validating, complemented and/or improving the current tool from the conceptual and practical point of view.

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Appendix A

Standard format for data collection.

Regarding the authors' experiences, a standard format is proposed to collect historical data, specifically intervention data, production data, and time data.

Appendix B

Integrated databases.

Graphical Analysis for Operation Management (GAOM) requires the development of two integrated databases, which relate the information in Tables VII and VIII. These databases are necessary for graphics construction.

In Table VIII, specifically for the first column (N_i), the data are supplemented with a sign (*) or (**), the first one related to corrective interventions and the second one to preventive interventions. The data without a sign will correspond to an operational intervention.

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RELIABILITY STOCHASTIC MODELING FOR REPAIRABLE PHYSICAL ASSETS. CASE STUDY APPLIED TO THE CHILEAN MINING

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ABSTRACT:
The reliability modelling, calculating and projecting for industrial equipment and systems are today a basic and fundamental task for reliability and maintenance engineers, regardless of the nature or genetics of those industrial assets. In this paper, the stochastic models PRP, NHPP and GRP are explained in detail with the corresponding conceptual, mathematical and stochastic development. For each model, the respective conceptualization and parameterization is analysed in detail. The practical application is developed for a real case in the mining industry, which shows step by step the appropriate stochastic and mathematical development. Finally, this research becomes an analytical and explanatory procedure on the definition, calculation, methodology and criteria to be considered for industrial assets parameterization with partial or null post maintenance degradation.

Key Words: Reliability, Degradation, Repairable Assets, Simulation.

1. INTRODUCTION

The model and analysis of repairable equipment are of great importance, mainly in order to increase the performance oriented to reliability and maintenance as part of the cost reduction in this last item. A reparable system is defined as:

"*A system that, after failing to perform one or more of its functions satisfactorily, can be restored to fully satisfactory performance by any method other than replacement of the entire system*" [1].

Depending on the type of maintenance given to equipment, is possible to find 5 cases [2]:

a) Perfect maintenance or reparation: Maintenance operation that restores the equipment to the condition "as good as new".
b) Minimum maintenance or reparation: Maintenance operation that restores the equipment to the condition "as bad as old".
c) Imperfect maintenance or reparation: Maintenance operation that restores the equipment to the condition "worse than new but better than old.
d) Over-perfect maintenance or reparation: Maintenance operation that restores the equipment to the condition "better than new"
e) Destructive Maintenance or reparation: Maintenance operation that restores the equipment to the condition "worse that old".

For a perfect maintenance, the most common developed model corresponds to the Perfect Renewal Process (PRP). In it, we assume that repairing action restores the equipment to a condition as good as new and assumes that times between failures in the equipment are distributed by an identical and independent way. The most used and common model PRP is the Homogeneous Processes of Poison (HPP), which considers that the system not ages neither spoils, independently of the previous pattern of failures. That is to say, it is a process without memory. Regarding case b), "as bad as old" is the opposite case to what happens in case a) "as good as new", since it is assumed that the equipment will stay after the maintenance intervention in the same state than before each failure. This consideration is based that the equipment is complex, composed by hundreds of components, with many failure modes and the fact that replacing or repairing a determined component will not affect significantly the global state and age of the equipment. In other words, the system is subject to minimum repairs, which does not cause any change or considerable improvement. The most common model to represent this case is through Non –Homogeneous Processes of Poison (NHPP), in this case the most used model to represent NHPP is called "Power Law". In this model, it is assumed a Weibull distribution for the first failure, that later it is modified over time.

Although the models HPP and NHPP are the most used, they have a practical restriction regarding its application, since a more realistic condition after a repairing action is what we find between both: "worse than new but better than old". In order to find a generalization to this situation and not distinguish between HPP and NHPP it was necessary to create the Generalized Renewal Process (GRP) [3], which establishes an improvement ratio. Unfortunately, the incorporation of this variable can complicate the analytic calculation of parameters and adjustments of probability. Therefore, its applicability in mathematic terms is complex. For this reason, it has been considered solutions through the Monte Carlo simulation (MC) being one of the most validated methods according the proposal developed by author Krivstov [4] where time series of good functioning are generated through the use of the inverse function of the probability distribution (pdf) that has as a base a random variable.

Understanding the importance and applicability of methods PRP, NHPP and GRP this paper introduces the conceptual, mathematical and stochastic development for each one, as explained and presented briefly in the previous paragraphs. Each model is explained and developed in the following way: conceptualization and parameterizing. In addition, each model will be complemented with a numerical application, specifically it correspond to 2 pulp pumps (water, copper concentrate and inert material) used in the mining industry of Chile, which suffer different levels of erosion due to use intensity, geographic height and of course according to the maintenance type developed in its life, planned or not planned (preventive or corrective maintenance).

With the above, this article begins by introducing stochastic models (PRP, NHPP and GRP), then is presented a brief of parameterization processes and a numerical analysis application. Finally, the paper concludes by summarizing the main lines provided by the article and its application to the industrial sector. Note the innovative contribution of this article involving the applicability of IT tools in resolving existing models. Such applicability is presented here as a sample, and with a specific real case of Chilean mining.

Notations	
PRP:	Perfect Renewal Process
NHPP:	Non-Homogeneous Poisson Process
GRP:	Generalized Renewal Process
$\lambda(t)$:	Failure Rate of an element in a given time t
t_i:	Function time between failure i-1 and i-th
$f(t)$:	Probability density function of failure (pdf) of an element with operation time t
$F(t)$:	Probability density function of accumulated failure of an element with operation time.
$\Gamma(\cdot)$:	Gamma function.
$f(t;\theta)$:	Probability density function of failure of an element with operation time t, with forma and scale parameters given by vector 0.
$L(\theta)$	Likelihood function for parameters vector 0 in a pdf given.
MTTF:	Mean time to failure.
MTTR:	Mean time to repair.
$\hat{a}$:	Estimated value of the parameter a (applicable for all parameters).
A_n:	Virtual age of system at the immediate moment of the repair of n-th.
T_n:	Virtual age (of operation) at the immediate moment of the repair of n-th.
q:	Parameter which establishes the defect of the repair.
TOL:	Numeric grade to consider acceptable a distribution adjustment through the likelihood maximum.
TQ:	Tolerance that corresponds to higher or lower percentage of the possibilities of value q.

Table1: Notation.

With the intention of highlighting the scientific and technical contribution of this article is necessary to emphasize in this introduction the following considerations: The wide range and variability of their behaviour requires the application of techniques of varying complexity and depth, that can adapt to the best way to each of the realities. The variable that defines and conditions the use of techniques is the state assets remaining after repair.

In this regard, there are five classifications repair: Perfect, minimal, imperfect, over- perfect and destructive. For perfect maintenance, it is used and recommended Perfect Renewal Process model (PRP) through homogeneous Poisson processes (HPP). For minimal repair, generally it represented by Nonhomogeneous Poisson Process (NHPP), the most widely used is "Power Law" model. However the great application of the aforementioned models, there are various situations that are not covered, since the most of cases repair are between the perfect and minimum condition (imperfect repair). For these situations, it enunciates and develops the "Generalized Renewal Model" (GRP). Moreover, since the probability of finding the values that give the maximum overall function of maximum likelihood is virtually zero by the random search, it is necessary to define a tolerance value for the partial derivatives ($\partial L/\partial B$ and $\partial L/\partial q$) that they are matched to zero, setting this tolerance value "TOL" as an acceptable range to consider adjusting distribution. For this, the simulation techniques and especially Monte Carlo emerge as a powerful alternative for resolution. It is recommended to check references [5 and 9] to study in details some advantages and defects about the models.

2. PRESENTATION OF THE STOCHASTIC MODELS

2.1. Perfect Renewal Process (PRP)

PRP Conceptualization

The Perfect Renewal Process model describes the situation in which a repairable system is restored to a state "as good as new" and the times between failures are considered independent and identically distributed. This process assumes that the equipment restores to an identical condition to the original, as if it is replaced. The graph of the failure rate depending on the time elapsed for equipment with growing failure rate, considering the general case of a Weibull distribution, would be the following in figure 1.

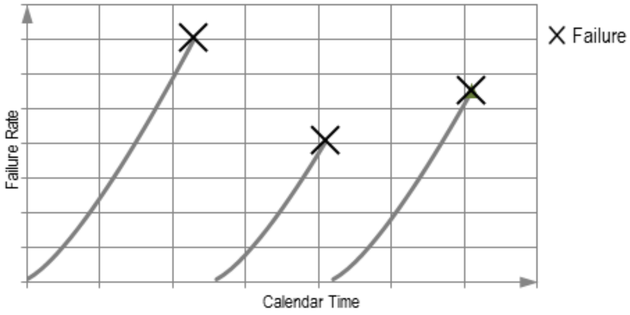


Fig. 1: Failure rate λ(t) in PRP (Source: own elaboration)

As proved in the former graphic, the evolution of the failure rate is reset after each failure, evidently due to fact that the equipment remains in perfect conditions. The PRP model possesses main application over those equipment that have a complete maintenance over all its components or if it a 100% replacement of the equipment.

In mathematical terms: Be t_i the functioning time between failures *i-l* and the *i-th*. Then, under a PRP model, any time t_i will obey to the same probability distribution with inalterable parameters in time, for example for the two-parameter Weibull case:

$$f(t_i) = \begin{cases} \dfrac{\beta}{\alpha}\left(\dfrac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} & t \geq 0 \\ 0 & t < 0 \end{cases}$$

Being α and β continuous and inalterable in time. The origin of this type of distribution is in order to consider increasing or decreasing failure rates along the time from the last repair. Being α and β the scale and form parameters respectively.

PRP Parameterization Model –Two- parameters Weibull

From a practical point of view, it is characterized by having 2 parameters, where β corresponds to the form parameter linked to the well-known bath curve and to the respective phase of life cycle of the asset, and the parameter α known as the scale parameter, which is linked directly with the variability and dispersion of the life data that the asset analysed has. The probability density function of failure (pdf) corresponds to (1):

$$f(t)=\frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \qquad (1)$$

In this case the failure rate is defined as (2):

$$\lambda(t)=\frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \qquad (2)$$

The mean time to failure (MTTF) and reliability *R(t)* are (3):

$$MTTF=\alpha\cdot\Gamma\left(1+\frac{1}{\beta}\right),\quad R(t)=e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \qquad (3)$$

Note that *Γ( )* corresponds gamma function (4):

$$\Gamma(t)=\int_{0}^{\infty} x^{t-1}e^{-x}\,dx \qquad (4)$$

The Weibull function itself is a generalization for the Exponential function, knowing that β=1, α=1/λ and γ=0. With Weibull distribution it is possible to represent the state of the asset for any of 3 phases in the bathtub curve (life cycle perspective): infant mortality, useful life or life wear out. For parameterization it is required a maximum likelihood function resolution, then a natural logarithm is applied partially with respect to each parameter to finally derived its and equals to zero. It is presented in (5) and (6):

$$\boxed{\alpha=\left(\frac{-\sum_{i=1}^{n}\left[t_i^{\beta}\right]}{n}\right)^{1/\beta}} \qquad (5)$$

$$\boxed{\frac{n}{\beta}+\sum_{i=1}^{n}\left[\ln\left[t_i\right]\right]=\left(\frac{n\sum_{i=1}^{n}\left[t_i^{\beta}\ln\left(t_i\right)\right]}{\sum_{i=1}^{n}\left[t_i^{\beta}\right]}\right)} \qquad (6)$$

For the resolution of this type of adjustment, there are specialized software applications. One of these is RelPro [14] which disposes of advanced and efficient algorithm for the resolution of this kind of problems. Also, in case of need to clarify and expand the concepts handled here, the following references are recommended [15, 16].

2.2. Non-Homogeneous Poisson Process

NHPP Conceptualization

NHPP is a Poisson process with a parametric model used to represent events with an occurrence of evolutional failure in time and always with the same tendency.

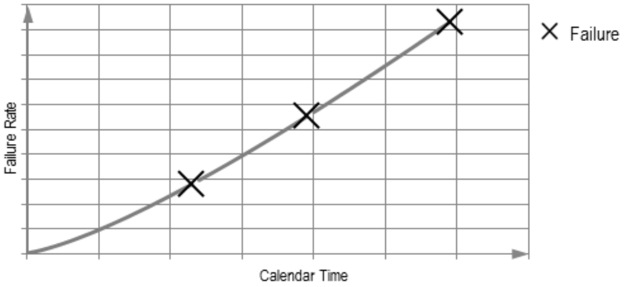


Fig. 2: Failure rate λ(t) in NHPP (Source: own elaboration)

This case applies specially for those equipment that are composed by many components where the replacement of one of them does not affect the global reliability: consider an equipment composed by hundreds of component that work in series, if one of them fails, this component is replaced and the equipment continues working but with a level of waste almost identical to previous one. For this reason the NHPP model applies for the called "minimum maintenance".

Next, figure 2 presents the graph for the behaviour of the failure rate over time, being this completely accumulative between one and other failure. As we appreciate in the former graphic, for the case of NHPP, the failure rate remains dependent on total time elapsed.

In the case of NHPP, the functions of the reliability and failure probability are expressed as follows (fig. 3).

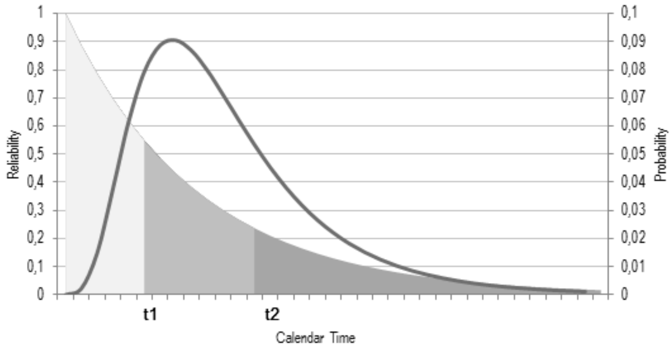


Fig. 3: R(t) and f(t) in NHPP (Source: own elaboration)

Having as a base the former graphic, let's consider that one equipment has a failure in a t_1 time. After being repaired, the functioning is restarted and begins to work in that same point. Then, the reliability function from t_1, for a t time that represents the elapsed time beyond t_1, will be gives as (7).

$$R(t \mid t > t_1) = \frac{R(t)}{R(t_1)} = 1 - F(t \mid t > t_1) \qquad (7)$$

This is called by various authors [15] as "Mission Time", where t corresponds to elapsed calendar time.

For a Weibull distribution, from the previous equation and since t_{i-1} corresponds to the total time elapsed until the last failure, and t_i the total time (calendar) elapsed after generate the failure *i-th*, will be possible to conclude the following probability density function (8):

$$f(t_i \mid t_i > t_{i-1}) = \frac{\beta}{\alpha}\left(\frac{t_i}{\alpha}\right)^{\beta-1} \exp\left\{\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right\} \qquad (8)$$

NHPP Parameterization Model – Weibull 2 parameters

In order to obtain the parameters α and β, the lineal regression is not a choice. It is ideally made an adjustment by maximum likelihood. The likelihood function is expressed as (9):

$$P(x_i \text{ en } [\mathrm{x_i}, \mathrm{x_i}+\mathrm{dx}] \ \forall \mathrm{i} \in \{1,..,\mathrm{n}\}) = \prod_{i=1}^{n} f(x_i;\theta)$$

$$L(\theta) = \prod_{i=1}^{n} f(x_i;\theta) \qquad (9)$$

Where Θ correspond to the vector of the parameters of distribution to which obey the *f(t)*. Moreover xi corresponds to the element *i-th* of the sample. As it is wished to obtain maximum likelihood between the data and one pdf: *f (t;Θ)*, the values of the vector Θ are adjusted with the aim to reach that maximum. Conceptually, parameters are searched in order to better fit to a sample $X_i,\ldots,X_n$ in such way that the probability of the series of values that be presented in a random sample be maximal:

Thus, in the present case with the simplified likelihood function and after applying and partial derivatives equal to zero, the results of the estimators for NHPP are (10) and (11):

$$\hat{\alpha} = \frac{t_n}{n^{1/\beta}} \qquad (10)$$

$$\hat{\beta} = \frac{n-1}{\sum_{i=1}^{n-1} \ln\left(\frac{t_n}{t_i}\right)} \qquad (11)$$

Where t_i corresponds to the elapsed time until the failure *i-th* and t_n the elapsed time until the last failure. As in the previous case, if it is needed to clarify and expand the concepts handled here, next references are recommended [15] y [16].

2.3. Generalized Renewal Process (GRP)

GRP Conceptualization

The traditional models already shown are only able to model 2 types of maintenance: the completely perfect and the completely imperfect. GRP model is the generalization for any level of perfection that has the maintenance, including the both mentioned. GRP adds a new parameter, called “virtual age”. The parameter A_n represents the age of the system at the immediate instant when the *n-th* repair is carried out. In this way, if $A_n = y$, the element has a time of functioning associated to a probability distribution conditioned for this age y. That is to say, all the failure times have different probability distributions as the time passes by.

Graphically, the failure rate evolves as is shown figure 4.

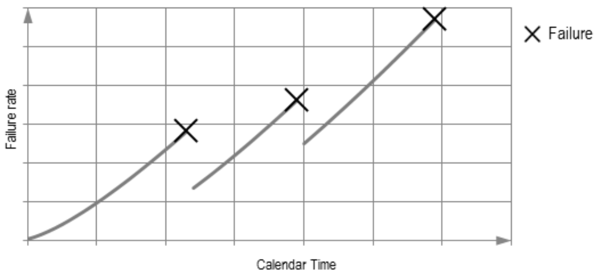


Fig. 4: Failure rate λ(t) in GRP (Source: own elaboration)

The way to incorporate this variable is considering that equipment begins to operate with certain waste, which is reflected in the reliability function. In this manner, the accumulated reliability and probability distribution for t_{n+1} is (12):

$$F(t \mid A_n = y) = \frac{F(t+y) - F(y)}{1 - F(y)}$$

$$R(t \mid A_n = y) = \frac{R(t+y)}{R(t)} \qquad (12)$$

By this way, it is clear that this “virtual age” is the age of waste in which the equipment begins to work again. The reliability function remains similar to the “Mission Time” only that this does not correspond to a real time elapsed, but to an equivalent. X_i is the *i-th* time of good functioning and T_n the total accumulated time elapsed until failure *n-th*, as follow (13):

$$T_n = \sum_{i=1}^{n} x_i \qquad (13)$$

Moreover, the parameter A_n is given by (14):

$$A_n = A_{n-1} + q \cdot x_n \qquad (14)$$

Using (13), then would be (15):

$$A_n = qT_n = q\sum_{i=1}^{n} x_i \qquad (15)$$

Where q is the parameter that decides the ineffectiveness of the repair, in this way q=0 implies that A_n =0, that is to say virtual age equal to 0. Therefore $q=0$ correspond to a perfect repair case, that is to say is completely effective. In the case it was q=1 then it begins to operate in the same part of the reliability function where the equipment failed. This would be (16):

$$\begin{aligned} &0 < q < 1 : \text{GRP} \\ &q = 0 \quad : \text{PRP (HPP)} \\ &q = 1 \quad : \text{NHPP} \end{aligned} \qquad (16)$$

Plotting the existing relation between real life and virtual age that evolves, it is possible to generate (see figure 5) the following comparative graphic for PRP, NHPP and GRP.

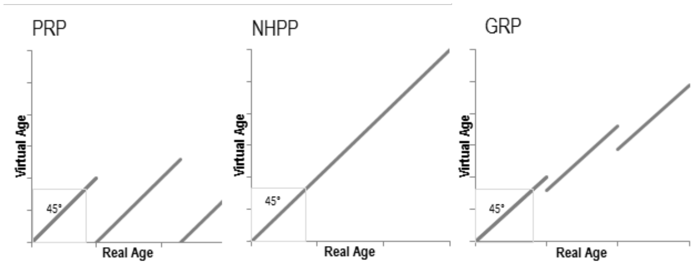


Fig. 5: Virtual age V/S Real age in PRP, NHPP y GRP (Source: own elaboration)

As in NHPP, it is determined the conditioned reliability and the respective pdf. Then, reliability will be modeled according to (17), (18) and (19):

$$R(t_i \mid t_i > q\cdot t_{i-1}) = \frac{e^{-\left(\frac{t_i}{\alpha}\right)^{\beta}}}{e^{-\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}}} \qquad (17)$$

$$F(t_i \mid t_i > q\cdot t_{i-1}) = 1 - e^{\left(\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right)} \qquad (18)$$

$$f(t_i \mid t_i > q\cdot t_{i-1}) = \frac{\beta}{\alpha}\left(\frac{t_i}{\alpha}\right)^{\beta-1} e^{\left(\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right)} \qquad (19)$$

Parameterization Model GRP

The adjustment developed is on the basis of a pdf with two-parameter Weibull (α, β), and adding the parameter q, so then we have 3 parameters to determine. The most common approach for parameters determination, by maximum likelihood, corresponds to the Likelihood Function. In order to solve this, a partial derivative in each variable is applied, then will be obtained a set of 3 equations with 3 unknown quantities, these are: α, β, q.

The parameters α, β, q are the 3 values to identify. Searching these parameters is a very exhaustive procedure, as it requires more precision in the procedure, generally is a long process, so it is suggested to use the Monte Carlo simulation. The searching of α, β, q starts with the simulation of q and β, repeated by uniform distributions (20):

$$\begin{aligned} q &\sim U[0,1] \\ \beta &\sim U[0,10] \end{aligned} \qquad (20)$$

Similarly, the estimated parameter $\hat{\alpha}$ for the GRP model yields (21):

$$\hat{\alpha} = \sqrt[\beta]{\frac{\sum_{i=2}^{n}\left[\left(t_i + t_{i-1}\left(q-1\right)\right)^{\beta} - \left(q \cdot t_{i-1}\right)^{\beta}\right] + t_1^{\beta}}{n}} \qquad (21)$$

Then, the procedure for the GRP adjustment is plotted through the following diagram of process. See Figure 6.

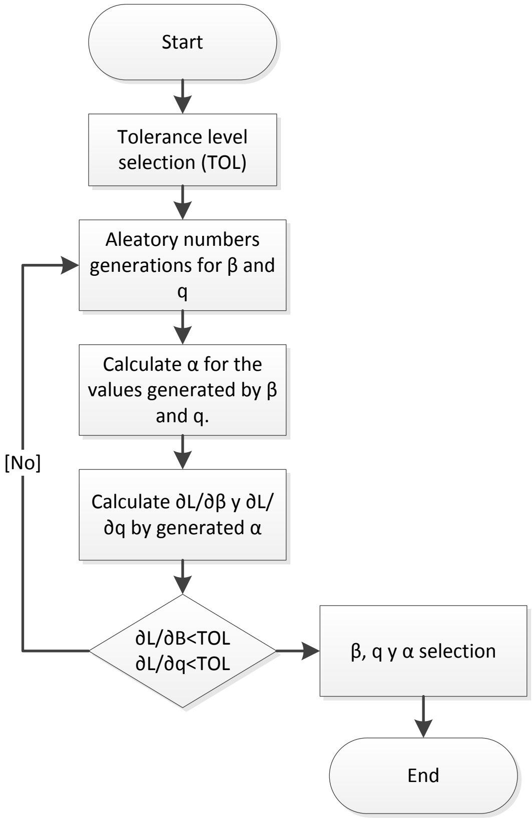


Fig. 6: Process diagram for GRP modelling (Source: own elaboration)

As far as the probability to find the values that grant the global maximum of the maximum likelihood function is virtually invalid through random search, it is necessary to define a value of tolerance for the partial derivatives ($\partial L/\partial B$ and $\partial L/\partial q$) equal to 0, being necessary to fix this value of tolerance "TOL" as an acceptable rank to consider that is found in a global maximum and in this way to accept the respective distribution adjustment.

Considering the adding of a new parameter, in this case q, always the adjustment GRP will give a higher likelihood than a PRP or NHPP adjustment. Nevertheless, in order to consider the existence and applicability of these cases, it is necessary to count on selection criteria. This is applied after the adjustment through GRP once obtained the parameter *q*.

As *q* value is always a continuous value, the probability to be exactly *q*=1 or *q*=0 is practically null, therefore it is considered a new tolerance level, which has been called TQ. This tolerance level corresponds to higher and lower percentage of the possibilities that value q has. The reason of this value (*q* parameter) is to identify when would be more appropriate to consider a PRP or NHPP model. Therefore the practical expression corresponds to (22):

$$\begin{array}{ll} 0+TQ<q<1-TQ & :\mathrm{GRP} \\ q\leq TQ & :\mathrm{PRP} \\ q\geq 1-TQ & :\mathrm{NHPP} \end{array} \qquad (22)$$

As in previous case, to clarify and expand the concepts handled here, references [15 and 16] are recommended.

3. NUMERICAL APPLICATION

According to preliminary conceptual and analytical development, it proceeds to develop a practical application, which corresponds to the analysis of a slurry pump (inert material), ID code: P01, it belongs to a process involved in copper mining. The model to be applied corresponds to GRP, given the flexibility and ability to generalize and discriminate any of the 3 models exposed PRP, NHPP and GRP. Table 2 shows the time records of good performance which have been collected by the entity performing industrial activity, and will be considered as the input data for the simulation. In order to understand and analyse the applicability of the methodology presented and its effects, the selected item is enough. Then, it proceeds to develop the probability distribution adjustment.

N° of Failure	Operating time [h]	N° of Failure	Operating time [h]
1	860,05	13	367,41
2	1608,24	14	2757,98
3	1134,24	15	355,50
4	2703,12	16	1084,39
5	645,38	17	855,52
6	95,15	18	280,52
7	1278,48	19	490,48
8	605,34	20	945,55
9	344,33	21	105,32
10	1054,68	22	127,33
11	680,57	23	61,85
12	405,38	24	326,30

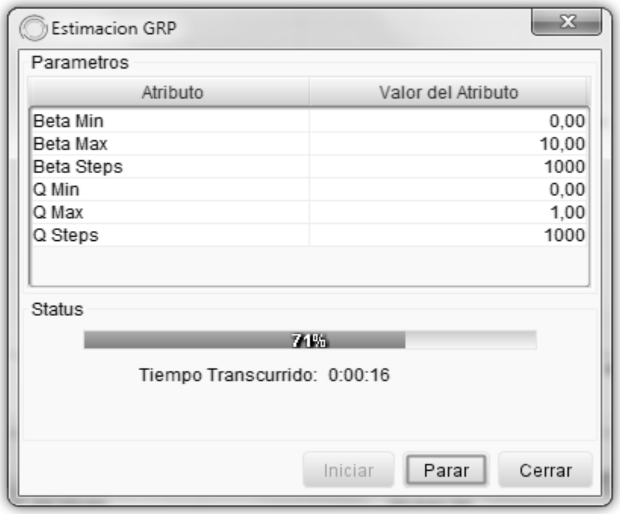
Table. 2: Time between failures for pump P01 [hours]. (Source: own elaboration)

Step 1: Tolerance level

Must be defined the tolerance level for the partial derivatives as TOL = 0.01 and tolerance for the q value is TQ = 5 %.

Step 2: Distribution parameterization

Once tolerance level is defined, it proceeds to apply GRP model. For this, it is decided to use a computer tool: RelPro®. It has been developed from the perspective of research and industrial application. Solving the equations with RelPro®, the following parameters are obtained. See Figures 7 and 8 respectively.


Estimacion GRP

Parametros

Atributo	Valor del Atributo
Beta Min	0,00
Beta Max	10,00
Beta Steps	1000
Q Min	0,00
Q Max	1,00
Q Steps	1000

Status

71%

Tiempo Transcurrido: 0:00:16

Fig. 7: Parameterization process for GRP, RelPro® Software. (Source: own elaboration)


Estimacion GRP

Parametros

Atributo	Valor del Atributo
Beta M	0,00
Beta M	10,00
Beta S	1000
Q Min	0,00
Q Max	1,00
Q Step	1000

Status

GRP Resultado

Optimos encontrados:
Alpha : 1968.067
Beta : 2.026
Q : 0.192
Modelo: GRP
Desea utilizar el modelo encontrado?

Fig. 8: Parameter estimation adjustment in GRP. RelPro® Software. (Source: own elaboration)

From the parameters obtained (α =1986,067; β =2,026 and q=0,192), the partial derivatives are solved and the acceptance of GRP distribution adjustment and level of tolerance are verified properly (23).

$$\left|\frac{\partial[\ln(L)]}{\partial\beta}\right| = 1{,}76\times10^{-7} < TOL = 0{,}01$$

$$\left|\frac{\partial[\ln(L)]}{\partial q}\right| = 0{,}009833 < TOL = 0{,}01 \qquad (23)$$

Regarding the q value, it has to (24):

$$TQ = 0{,}05 < q = 0{,}192 < 1 - TQ = 0{,}95 \qquad (24)$$

Therefore, determining an acceptable adjustment solution by maximum likelihood with partial derivatives (quality guarantee of the fit), and a q parameter with a numeric value between the range 0.05 < q <0.95, it is possible to affirm that the use of GRP model is suitable for the case. For this, the use of a traditional adjustment would be completely incorrect.

Step 3: Analysis

With this result, one possible analysis is to project (correctly) the equipment failures, and indirectly the rate of increase of the frequency of failure and the decreasing of operation times.

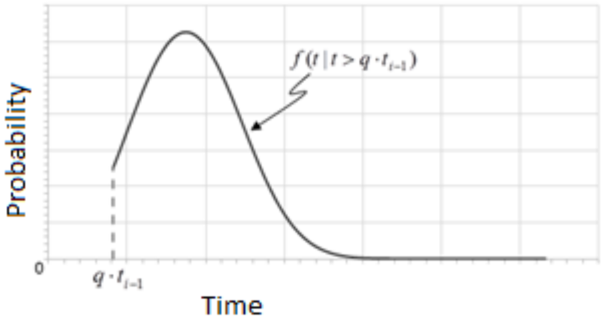


Fig. 9: P.D.F. of GRP model, for elapsed time t $_{i-1}$. RelPro® Software. (Source: own elaboration)

The expected time of correct performance, at the previous instant than the operation is recovery (after failure), it is determined by the difference between the expectancy of probability density function (based on the total elapsed time) and the virtual age of the asset. Graphically, Figures 9 and 10 represent it.

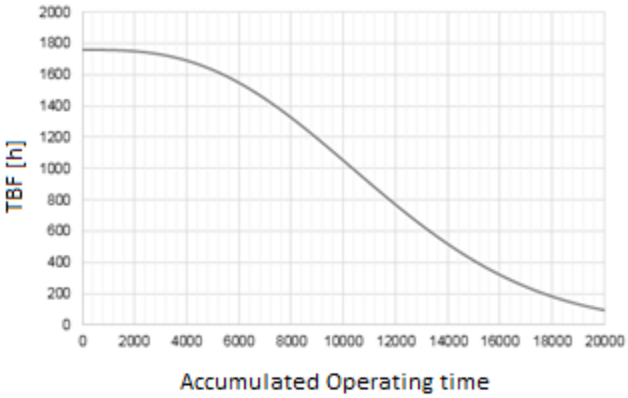


Fig. 10: Expected TBF according to the operating time elapsed until the last intervention. RelPro® Software. (Source: own elaboration)

To estimate the number of accumulated failures over time, it is possible to consider that the first failure occurs at the MTBF, expected value at the beginning of the operation of the equipment. Thus it is possible to project recursively with the expected MTBF then every occurrence of failure. Obviously, this is a generalization and simplification of the problem. Finally, it is possible to obtain the graph of cumulative number of events for a total time of operation. See Figure 11 with the fault behaviour accumulated v/s total time of operation. Clearly a rising trend and accelerated failure time less operation is identified. This is understood as active aging in time. Analytically (25) to (30):

$$E[t_i \mid t_i > q \cdot t_{i-1}] = \int_{q \cdot t_{i-1}}^{\infty} \left(f(t \mid t > q \cdot t_{i-1}) \times t \right) dt \qquad (25)$$

$$MTBF(t_{i-1}) = E[t_i \mid t_i > q \cdot t_{i-1}] - q \cdot t_{i-1} \quad (26)$$

$$MTBF(t_{i-1}) = \int_{q \cdot t_{i-1}}^{\infty} \left(f(t \mid t > q \cdot t_{i-1}) \times t \right) dt - q \cdot t_{i-1} \quad (27)$$

$$MTBF(t_{i-1}) = \int_{q \cdot t_{i-1}}^{\infty} \left(\frac{\beta}{\alpha} \left(\frac{t}{\alpha} \right)^{\beta-1} e^{\left(\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} - \left(\frac{t}{\alpha} \right)^{\beta} \right)} \times t \right) dt - q \cdot t_{i-1} \quad (28)$$

$$MTBF(t_{i-1}) = e^{\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta}} \times \int_{q \cdot t_{i-1}}^{\infty} \left(\frac{\beta}{\alpha} \left(\frac{t}{\alpha} \right)^{\beta-1} e^{\left(- \left(\frac{t}{\alpha} \right)^{\beta} \right)} \times t \right) dt - q \cdot t_{i-1} \quad (29)$$

$$s - 1 = \frac{1}{\beta} \Rightarrow s = \frac{1}{\beta} + 1$$

$$MTBF(t_{i-1}) = \alpha \times e^{\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta}} \times \underbrace{\int_{\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta}}^{\infty} \left(e^{(-p)} \times p^{s-1} \right) dp}_{\Gamma\left(s, \left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} \right)} - q \cdot t_{i-1}$$

$$MTBF(t_{i-1}) = e^{\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta}} \alpha \times \Gamma\left(\frac{1}{\beta} + 1, \left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} \right) - q \cdot t_{i-1}$$

$$MTBF(t_{i-1}) = \frac{\alpha \times \Gamma\left(\frac{1}{\beta} + 1, \left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} \right)}{R(t_{i-1})} - q \cdot t_{i-1} \quad (30)$$

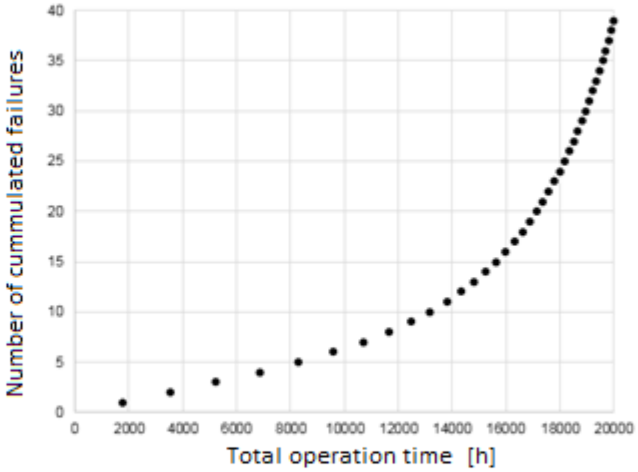


Fig. 11: Forecast for Number of Failures. RelPro® Software. (Source: own elaboration)

In addition, the software tool used (RelPro®) allows diagramming the time evolution curves: probability density function *f(t)*, the cumulative probability function *F(t)*, reliability *R(t)* and the failure rate *λ(t)*. See Figure 12.

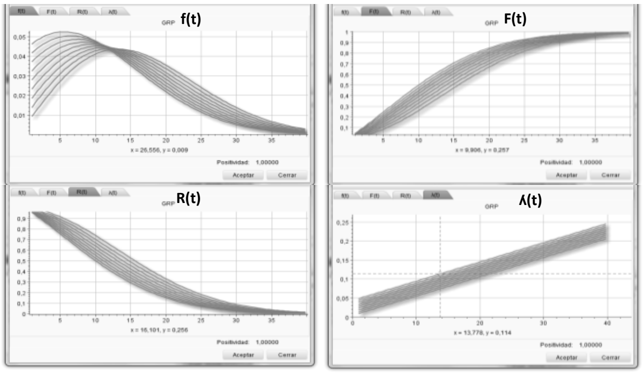


Fig. 12: Curves f(t), F(t), R(t) and λ(t), RelPro® Software. (Source: own elaboration)

By default, RelPro® graphs the curves which will come under the elements after the next nine events (internal standard). With this it is possible to note how quickly degrades element.

Analysing graphic curves in Figure 12, the deterioration of reliability curve after the occurrence of a failure is identified. At the same time it is possible to note that the curve of probability density function increases its density, approaching it every time to the origin values. For the failure rate, after each failure it is incremented in equivalent intervals.

4. FUTURE LINES OF APPLICATION

This methodology is focused on practical application, so further research may focus on different application examples for different types of machines (used in mining or in another sector). In such further applications, it may be interesting to specify the conditions of use of, which maintenance is carried out, the total operating time, utilization times, environmental or process conditions, etc. With this will be possible to compare the results obtained for both types of machinery according to different boundary conditions.

5. CONCLUSIONS

The reliability model is an essential aspect for the management and optimization of physical industrial assets. In order to learn in detail the step by step of each model is a fundamental task to apply effective and correctly each model. Diverse researches omit the process of resolution and only present final results indicating the use of a model and the use of some computed tool with integrated algorithm. It was identified in different researches, which motivated the research team to develop a specific conceptual pattern and resolution practical for each stochastic parametric model former mentioned. This is fundamental to recognize the value of this work and its contribution for future researchers who wish to learn and apply this knowledge. For this reason, this research becomes an analytic and explicative procedure about the definition, calculation methodology and criteria that must be considered to parameterize industrial assets under certain degradation level after maintenance, complementing in addition its analysis with a numeric application that allows demonstrating step by step the mathematic development as appropriate. The practical case was developed in mining industry of Chile.

It is worth mentioning here the frequent lack of feedback between users and manufacturers of equipment, resulting in ignorance by manufacturers about the real weaknesses of the machines. The performance of assets under ideal conditions (lab test) is extremely differences comparing with real process conditions.

As a second phase of this research for potential publication, the research team is analyzing a presorting to the respective parameter that presents the current article, which corresponds to the identification whether the model is nonparametric. The method is parametric (MP) if the modeling fits a probability distribution function known; on the other hand, if you cannot make this assumption, the method is nonparametric (MNP). There are also models that contain a portion of the parametric function and one not, these are the semi-parametric methods (MSP). The latter classification (MSP) is of great interest for research and application, since in practice generally the assets are subject to many variables that classical models not included in the modeling and analysis of failure rate, for example: operating temperature, workload, diagnosis of lubricants (parts per million), etc. These variables are not constant and can cause changes in the reliability of a component, which is necessary to analyze and quantify for designing an effective and efficient maintenance policy. In addition, it is expected to incorporate into the analysis the TRP model (Trend-Renewal-Process) [18], described and studied in detail by Lindqvist, Elvebakk and Heggland [19], this being a different model of imperfect repair, with similar characteristics to NHPP.

Modern methods allow modeling based on these environmental factors and stress, but they are bounded to assumptions or restrictions on the number of factors to analyze, which makes more complex application and obviously their systematic use in the reliability analysis.

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APPRECIATION

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Chapter 12

Mathematical and Stochastic Models for Reliability in Repairable Industrial Physical Assets

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ABSTRACT

Generally, assets present a varied behaviour in their life cycle, which is related directly to the use given and consequently related to the technical assistance traditionally known as maintenance or maintenance policies. It can be of a diverse nature: perfect, minimum, imperfect, over-perfect, and destructive as appropriate. This feature requires the application of advanced techniques in order to model the behaviour of assets life, adapting ideally to each reality of use and wear out. In this chapter, the stochastic models PRP, NHPP, and GRP are explained with their conceptual, mathematic, and stochastic development. For each model, the conceptualization, parameterizing, and stochastic simulation are analysed. Additionally, complementing the analysis and resolution pattern, these models are concluded with a numeric application that allows one to show step by step the mathematic and stochastic development as appropriate.

1. INTRODUCTION

The model and analysis of repairable equipments are of great importance, mainly in order to increase the performance oriented to reliability and maintenance as part of the cost reduction in this last item. A reparable system is defined as:

> *A system that, after failing to perform one or more of its functions satisfactorily, can be restored to fully satisfactory performance by any method other than replacement of the entire system. (Ascher & Feingold, 1984)*

> *A system that, after failing in order to develop an activity properly, is possible to restore satisfac-*

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torily its functioning by some method. (Ascher & Feingold, 1984)

Depending on the type of maintenance given to an equipment, is possible to find 5 cases (Veber et al., 2008):

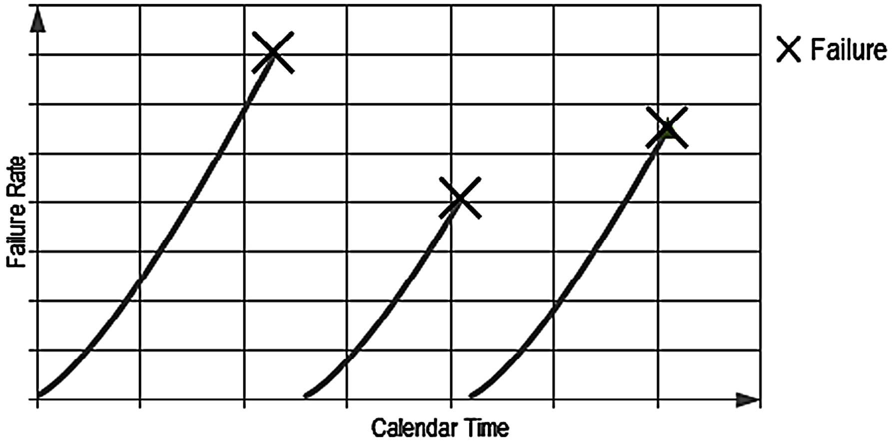
1. **Perfect Maintenance or Reparation:** Maintenance operation that restores the equipment to the condition "as good as new".
2. **Minimum Maintenance or Reparation:** Maintenance operation that restores the equipment to the condition "as bad as old".
3. **Imperfect Maintenance or Reparation:** Maintenance operation that restores the equipment to the condition "worse than new but better than old".
4. **Over-Perfect Maintenance or Reparation:** Maintenance operation that restores the equipment to the condition "better than new"
5. **Destructive Maintenance or Reparation:** Maintenance operation that restores the equipment to the condition "worse that old".

For a perfect maintenance, the most common developed model corresponds to the Perfect Renewal Process (PRP). In it, we assume that repairing action restores the equipment to a condition as good as new and assumes that times between failures in the equipment are distributed by an identical and independent way. The most used and common model PRP is the Homogeneous Processes of Poison (HPP), which considers that the system not ages neither spoils, independently of the previous pattern of failures. That is to say, it is a process without memory. Regarding case b), "as bad as old" is the opposite case to what happens in case a) "as good as new", since it is assumed that the equipment will stay after the maintenance intervention in the same state than before each failure. This consideration is based that the equipment is complex, composed by hundreds of components, with many failure modes and the fact that replacing or repairing a determined component will not affect significantly the global state and age of the equipment. In other words, the system is subject to minimum repairs, which does not cause any change or considerable improvement. The most common model to represent this case is through Non –Homogeneous Processes of Poison (NHPP), in this case the most used model to represent NHPP is called "Power Law". In this model, it is assumed a Weibull distribution for the first failure, that later it is modified over time.

Although the models HPP and NHPP are the most used, they have a practical restriction regarding its application, since a more realistic condition after a repairing action is what we find between both: "worse than new but better than old". In order to find a generalization to this situation and not distinguish between HPP and NHPP it was necessary to create the Generalized Renewal Process (GRP) (Kijim & Sumita, 1986), which establishes an improvement ratio. Unfortunately, the incorporation of this variable can complicate the analytic calculation of parameters and adjustments of probability. Therefore, its applicability in mathematic terms is complex. For this reason, it has been considered solutions through the Monte Carlo simulation (MC) being one of the most validated methods according the proposal developed by author Krivstov (2000) where time series of good functioning are generated through the use of the inverse function of the probability distribution (pdf) that has as a base a random variable.

Understanding the importance and applicability of methods PRP, NHPP and GRP this paper introduces the conceptual, mathematical and stochastic development for each one, as explained and presented briefly in the previous paragraphs. Each model is explained and developed in the following way: conceptualization, parameterising and stochastic simulation. In addition, each model will be complemented with a numerical application that allows to show step by step the mathematical and stochastic development as appropriate. The applied cases correspond to 3 pulp pumps (water,

Figure 1. Failure rate λ(t) in Perfect Renewal Process



copper concentrate and inert material) used in the mining industry of Chile, which suffer different levels of erosion due to use intensity, geographic height and of course according to the maintenance type developed in its life, planned or not planned.

2. DEFINITION OF THE STOCHASTIC MODELS

2.1 Perfect Renewal Process (PRP)

The Perfect Renewal Process model describes the situation in which a repairable system is restored to a state "as good as new" and the times between failures are considered independent and identically distributed. This process assumes that the equipment restores to an identical condition to the original, as if it is replaced.

The graph of the failure rate depending on the time elapsed for an equipment with growing failure rate, considering the general case of a Weibull distribution, would be according to Figure 1.

As proved in Figure 1, the evolution of the failure rate is reset after each failure, evidently due to fact that the equipment remains in perfect conditions. The PRP model possesses main application over those equipments that have a complete maintenance over all its components or if it a 100% replacement of the equipment.

In mathematical terms: Be *ti* the functioning time between failures i-l and the i-th. Then, under a PRP model, any time *ti* will obey to the same probability distribution with inalterable parameters in time, for example for the two-parameter Weibull case:

$$f(t_i) = \begin{cases} \dfrac{\beta}{\alpha}\left(\dfrac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} & t \geq 0 \\ 0 & t < 0 \end{cases}$$

Being α *and* β continuous and inalterable in time. The origin of this type of distribution is in order to consider increasing or decreasing failure rates along the time from the last repair. Being α *and* β the scale and form parameters respectively.

Parameterising of the PRP Model

Exponential Distribution

The density function of exponential probability correspond to the distribution that model the time between 2 random events described by a distribution of Poisson. The pdf correspond to Equation 1.

With statistical (shown in Equation 2).

Table 1. Time between failures of the pump 1 in hours

Number of Failure	Time between Failures [h]	Number of Failure	Time between Failures [h]
1	434,09	16	375,05
2	226,04	17	496,48
3	266,67	18	649,41
4	681,33	19	540,68
5	1127,85	20	491,59
6	634,69	21	947,31
7	474,84	22	718,78
8	38,72	23	953,63
9	31,89	24	182,2
10	711,52	25	391,55
11	726,9	26	327,71
12	574,15	27	986,04
13	1043,54	28	352,53
14	336,54	29	631,86
15	771,23	30	680,52

Table 2. Time between failures of pump P2 in hours

Number of Failure	Time between Failures [h]	Number of Failure	Time between Failures [h]
1	270,19	16	135,21
2	89,42	17	173,39
3	451,74	18	4,53
4	30,69	19	40,36
5	17,00	20	23,05
6	176,96	21	38,15
7	42,67	22	31,61
8	78,72	23	27,65
9	42,84	24	34,05
10	214,63	25	0,25
11	0,96	26	20,56
12	80,70	27	127,85
13	8,54	28	11,15
14	5,79	29	52,26
15	104,35	30	26,52

The exponential function is applied commonly over the time of good functioning, specifically for those equipment that are found in useful life phase, since this allows working with a mean rate of constant failure.

Equation 1. Pdf for exponential distribution

$$f(t) = \lambda e^{-\lambda t}; t \geq 0$$

Equation 2. Statistical of exponential distribution

$$E(t) = 1/\lambda,\ \sigma^2 = 1/\lambda^2$$

Equation 3. MTTF and reliability for exponential distribution

$$MTTF = 1/\lambda,\ R(t) = e^{-\lambda t}$$

Equation 4. Pdf for a two-parameter Weibull distribution

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

Equation 5. Failure rate for a two-parameter Weibull distribution

$$\lambda(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}$$

Equation 6. MTTF and reliability for a two-parameter Weibull distribution

$$MTTF = \alpha \cdot \Gamma\left(1 + \frac{1}{\beta}\right),\quad R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

Table 3. Time between failures of the pump P3 in hours

Number of Failure	Time between Failures [h]	Number of Failure	Time between Failures [h]
1	860,05	13	367,41
2	1608,24	14	2757,98
3	1134,24	15	355,50
4	2703,12	16	1084,39
5	645,38	17	855,52
6	95,15	18	280,52
7	1278,48	19	490,48
8	605,34	20	945,55
9	344,33	21	105,32
10	1054,68	22	127,33
11	680,57	23	61,85
12	405,38	24	326,30

Linking these parameters with mean time to failure (MTTF) and reliability R(t) these are defined as shown in Equation 3.

The reliability for the case of an exponential distribution is possible to derive it of the following way, understanding that failure rate is constant:

$$\frac{dR(t)}{dt} = -\lambda R(t)$$

$$\frac{dR(t)}{R(t)} = -\lambda dt$$

$$\int \frac{dR(t)}{R(t)} = \int -\lambda dt$$

$$\ln(R(t)) = -\lambda t$$

$$R(t) = e^{-\lambda t}$$

Is important to indicate that the failure rate concept corresponds to the rate or probability that elements fail and that have survived until a determined time *t*.

In order to obtain the mean life or MTTF according to the most appropriate term, is possible to reach it through the following analysis:

$$R(t) = e^{-\lambda t}$$

$$F(t) = 1 - R(t) = 1 - e^{-\lambda t}$$

$$f(t) = F'(t) = \lambda e^{-\lambda t}$$

$$MTTF = E\left[t\right] = \int_{0}^{\infty} \left(\lambda e^{-\lambda t} \times t\right) dt = \frac{1}{\lambda}$$

The data fitting or parameterising for an exponential function, using the method of Likelihood Maximum, is expressed in the following way:

$$P(x_i \text{ en } [\mathrm{x_i},\ \mathrm{x_i}+\mathrm{dx}]\forall \mathrm{i} \in \left\{1,..,\mathrm{n}\right\}) = \prod_{i=1}^{n} f(x_i;\theta)$$

$$L(\theta) = \prod_{i=1}^{n} f(x_i;\theta)$$

Resolving we have:

$$L = \left[\prod_{i=1}^{n} \left\{\lambda e^{-\lambda t_i}\right\}\right]$$

$$L = \lambda^n e^{\left(-\lambda \sum_{i=1}^{n} t_i\right)}$$

Then, it is applied the natural logarithm in order to simplify the expression:

$$\ln(L) = \ln(\lambda^n) + \ln\left\{ e^{-\lambda\sum_{i=1}^{n} t_i} \right\} =$$

$$n\ln(\lambda) + -\lambda\sum_{i=1}^{n} t_i$$

And finally, it is derived with respect to the adjusted parameter.

$$\frac{\partial \ln(L)}{\partial \lambda} = 0$$

$$\frac{\partial}{\partial \lambda}\left(n\ln(\lambda) + -\lambda\sum_{i=1}^{n} t_i \right) = 0$$

$$\left(n\frac{1}{\lambda} + -\sum_{i=1}^{n} t_i \right) = 0$$

$$\Rightarrow \lambda = \frac{n}{\left(\sum_{i=1}^{n} t_i \right)}$$

Then, the parameter L is equal to the multiplicative inverse of the average of times observed, that is to say the *mean rate* in which occurs the failure events.

Weibull Distribution

From a practical point of view, it is characterized by having 2 parameters, where β corresponds to the form parameter linked to the well-known bath curve and to the respective phase of life cycle of the asset, and the parameter *α* known as the scale parameter, which is linked directly with the variability and dispersion of the life data that the asset analyzed has. The probability density function of failure (pdf) corresponds to Equation 4.

In this case the failure rate is defined as shown in Equation 5.

The mean time to fail (MTTF) and reliability R (t) correspondingly are shown in Equation 6.

Note that Γ corresponds to the gamma function (Equation 7).

The case of the three-parameter Weibull distribution also exists. The addition of the third parameter to the Weibull distribution allows adjusting the location of the function, setting a minimum of lifetime γ in units of time, of course.

The addition of this parameter modifies the previous equations to the following form (Equations 8, 9, and 10).

The addition of this third parameter allows that the adjustment to the function of density of probability being more precise, achieving a major goodness of adjustment. The Weibull function for itself constitutes a generalization for the exponential function since for values of β=1 we have *α =*1/λ and *γ =0*

The adjustment through Weibull distribution allows representing the state of equipment in any of the 3 phases of the bath curve, through the adjustment of the parameter β that acts as a factor to the time *t* in the failure rate function.

For the parameterising, the function of likelihood maximum is expressed as:

$$P(x_i \text{ en } [\mathrm{x_i},\ \mathrm{x_i}+\mathrm{dx}]\forall \mathrm{i} \in \{1,..,\mathrm{n}\}) = \prod_{i=1}^{n} f(x_i;\theta)$$

$$L(\theta) = \prod_{i=1}^{n} f(x_i;\theta)$$

Nevertheless, resolving it is:

$$L(\theta \mid t_1,..,t_n) = \left[\prod_{i=1}^{n} \left\{ \frac{\beta}{\alpha}\left(\frac{t_i}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \right\} \right]$$

$$L(\theta \mid t_1,..,t_n) = \left(\frac{\beta}{\alpha^{\beta}}\right)^{n} \left[\prod_{i=1}^{n} \left\{ t_i^{\beta-1} e^{-\left(\frac{t_i}{\alpha}\right)^{\beta}} \right\} \right]$$

Then, it is applied the natural logarithm (shown in Box 1).

Then, it is derived partially with respect of each parameter and equalize to 0. This is:

Equation 7. Gamma function

$$\Gamma(t)=\int_{0}^{\infty}x^{t-1}e^{-x}dx$$

Equation 8. Pdf for a three-parameter Weibull distribution

$$f(t)=\frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1}e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}}$$

Equation 9. Failure rate for a three-parameter Weibull distribution

$$\lambda(t)=\frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1}$$

Equation 10. MTTF and reliability for a three-parameter Weibull distribution

$$MTTF=\gamma+\alpha\cdot\Gamma\left(1+\frac{1}{\beta}\right),\quad R(t)=e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}}$$

$$\frac{\partial}{\partial\theta}\ln\left[L(\theta\mid t_1,..,t_n)\right]=0$$

Derived partial over *α* (Box 2).

And then the partial derivative over β (shown in Box 3).

With this, it is used the equivalence of (1) and it is replaced in the former equation to obtain finally:

$$\boxed{\frac{n}{\beta}+\sum_{i=1}^{n}\left[\ln\left[t_i\right]\right]=\left(\frac{n\sum_{i=1}^{n}\left[t_i^{\beta}\ln\left(t_i\right)\right]}{\sum_{i=1}^{n}\left[t_i^{\beta}\right]}\right)}\,(2)$$

For the resolution of this type of adjustment, there are specialized softwares. One of these is RelPro (2014) which disposes of advanced and efficient algorithm for the resolution of this kind of problems. The advantages of this tool is the flexibility of analysis of different stochastic models, the potential analysis post parameterising, the usage and fast learning of the user and evidently the capacity to model, analyze and simulate simple and complex systems. RelPro solves the equation (2) for random search over the parameter β and then obtaining this parameter, it is replaced in the equation (1) and it is obtained the parameter *a*.

Box 1.

$$\ln\left[L(\theta \mid t_1,..,t_n)\right] = \ln\left[\left(\frac{\beta}{\alpha^{\beta}}\right)^{n}\right] + \sum_{i=1}^{n}\left[\ln\left[t_i^{\beta-1} e^{-\left(\frac{t_i}{\alpha}\right)^{\beta}}\right]\right]$$

$$\ln\left[L(\theta \mid t_1,..,t_n)\right] = n\ln\left[\left(\frac{\beta}{\alpha^{\beta}}\right)\right] + \sum_{i=1}^{n}\left[\ln\left[t_i^{\beta-1}\right] - \left(\frac{t_i}{\alpha}\right)^{\beta}\right]$$

$$\ln\left[L(\theta \mid t_1,..,t_n)\right] = n\left(\ln\left[\beta\right] - \beta\ln\left[\alpha\right]\right) + \sum_{i=1}^{n}\left[\ln\left[t_i^{\beta-1}\right]\right] - \sum_{i=1}^{n}\left[\left(\frac{t_i}{\alpha}\right)^{\beta}\right]$$

Box 2.

$$\frac{\partial}{\partial\alpha}\left(n\left(\ln\left[\beta\right] - \beta\ln\left[\alpha\right]\right) + \left(\beta-1\right)\sum_{i=1}^{n}\left[\ln\left[t_i\right]\right] - \sum_{i=1}^{n}\left[\left(\frac{t_i}{\alpha}\right)^{\beta}\right]\right) = 0$$

$$n\left(\frac{-\beta}{\alpha}\right) - \beta\alpha^{-(\beta+1)}\sum_{i=1}^{n}\left[t_i^{\beta}\right] = 0$$

$$\frac{-n}{\alpha^{-\beta}} = \sum_{i=1}^{n}\left[t_i^{\beta}\right]$$

$$\boxed{\alpha = \left(\frac{-\sum_{i=1}^{n}\left[t_i^{\beta}\right]}{n}\right)^{1/\beta}} \quad (1)$$

Box 3.

$$\frac{\partial}{\partial\beta}\left(n\left(\ln\left[\beta\right] - \beta\ln\left[\alpha\right]\right) + \left(\beta-1\right)\sum_{i=1}^{n}\left[\ln\left[t_i\right]\right] - \sum_{i=1}^{n}\left[\left(\frac{t_i}{\alpha}\right)^{\beta}\right]\right) = 0$$

$$n\left(\frac{1}{\beta} - \ln\left[\alpha\right]\right) + \sum_{i=1}^{n}\left[\ln\left[t_i\right]\right] = \left(\alpha^{-\beta}\left(\ln\left(\alpha\right)\sum_{i=1}^{n}\left[t_i^{\beta}\right] - \sum_{i=1}^{n}\left[t_i^{\beta}\ln\left(t_i\right)\right]\right)\right) = 0$$

$$n\left(\frac{1}{\beta} - \ln\left[\alpha\right]\right) + \sum_{i=1}^{n}\left[\ln\left[t_i\right]\right] = \left(-n\ln\left(\alpha\right) - \alpha^{-\beta}\sum_{i=1}^{n}\left[t_i^{\beta}\ln\left(t_i\right)\right]\right) = 0$$

Simulation for the PRP Model

The simulation of functioning times in equipment represented by the PRP model is relatively simple, and it is only necessary to develop the resolution process of the inverse function.

It is obtained the Weibull function.

$$F(t) = \int_0^\infty f(t) = \int_0^\infty \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^\beta} dt$$

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^\beta} = u$$

The accumulated distribution function is evidently distributed between 0 and 1.

The resolution of the random variable *t* in function of a variable evenly distributed could be:

$$F(t) = u \in U[0,1]$$

$$1 - e^{-\left(\frac{t}{\alpha}\right)^\beta} = u$$

$$e^{-\left(\frac{t}{\alpha}\right)^\beta} = 1 - u$$

$$\ln\left(e^{-\left(\frac{t}{\alpha}\right)^\beta}\right) = \ln(1-u)$$

$$\left(\frac{t}{\alpha}\right)^\beta = -\ln(1-u)$$

$$\frac{t}{\alpha} = \left(-\ln(1-u)\right)^{1/\beta}$$

$$\boxed{t = TBF = \alpha\left(-\ln(1-u)\right)^{1/\beta} \wedge u \in U[0,1]}$$

In this way, from the creation of a random variable μ, is possible to generate the respective values of *t*. Moreover, in this case as this is a complete renewal process, any *t* will be equivalent to a new time of simulated good functioning (TTF) knowing TTF as the time that the equipment operates without anomalies, according the applied usage profile.

Numeric Exemplification: PRP Case

The numeric case corresponds to the analysis of a pulp pump 1 (P1). According to Table 1 contains the time between failures records.

Then, in order to develop the respective adjustment of probability distribution, it is implemented step by step:

Step 1: Tendency Test

According the information shown in Table 1, for the pump 1 has been recorded 30 times between failures, in hours and in order of occurrence.

According to literature, it is necessary to develop a tendency test that allows determining quantitatively if the times of functioning of a system show a significate tendency, which can be an improvement or a degradation tendency. In this case it has been chosen the tendency test of Laplace (Nist/Sematech, 2014) optimum method to distinguish between "there is not tendency" or "there is tendency" following the model of exponential law NHPP. Among other tests there is the *Test of inverse order"* and the *"Test of military book of EEUU* (Nist/Sematech, 2014) both of them do not apply due to fact that they are for cases such as application of Duane Model (Duane, 1964).

The Laplace Test gives as result a statistician *z* that must be compared with the standard normal distribution, due to it approaches to a random variable. The statistician z is calculated as:

$$z = \frac{\frac{\sum_{i=1}^{n} t_i}{n} - \frac{t_o}{2}}{t_o\sqrt{\frac{1}{12n}}}$$

where

t_o: total time lapsed,
n: total number of times,

t_i: total time lapsed to the event i.

It is assumed that for statistician z:

$Z = 0$; without tendency

$z > 0$; tendency to spoilage

$z < 0$; tendency to improvement

Evaluating the expression, we obtain a z value=-0.0953.

From the standard normal distribution, considering a significance level equal to 0.10, the critical value is equal to 1.645. If $-1.645<z<1.645$ then, it is failed refusing the hypothesis that there is no tendency. Therefore, having a value z equal to -0.0953 is not possible to say that there is tendency in the data, therefore PRP modelling is applicable.

Step 2: Distribution Adjustment

Once the PRP modelling is appropriately justified (there is not tendency) it is proceeded to apply the distribution adjustment under the two-parameter Weibull distribution.

According to the method of maximum plausibility previously presented, the values of parameters $\{\alpha, \beta\}$ that give the maximal likelihood, are those that satisfy the following equations:

$$\hat{\alpha} = \left(\frac{\sum_{i=1}^{n} \left(t_i\right)^{\hat{\beta}}}{n} \right)^{1/\hat{\beta}}$$

$$\frac{\sum_{i=1}^{n} \left(t_i\right)^{\hat{\beta}} \ln(t_i)}{\sum_{i=1}^{n} \left(t_i\right)^{\hat{\beta}}} - \frac{1}{\hat{\beta}} = \frac{1}{n} \sum_{i=1}^{n} \ln\left(t_i\right)$$

Solving the equations through the software RelPro we have that the parameters are α=632.04 and β =1.99 respectively.

2.2 Non-Homogeneous Poisson Process

NHPP is a Poisson process with a parametric model used to represent events with an occurrence of evolutional failure in time and always with the same tendency. This case applies specially for those equipments that are composed by many components where the replacement of one of them does not affect the global reliability: consider an equipment composed by hundreds of component that work in series, if one of them fails, this component is replaced and the equipment continues working but with a level of waste almost identical to previous one. For this reason the NHPP model applies for the called "minimum maintenance"

Next, in Figure 2 is presented the graph for the behaviour of the failure rate in time, being this completely accumulative between one and other failure.

As we appreciate in the former graphic, for the case of NHPP, the failure rate remains dependent on total time elapsed.

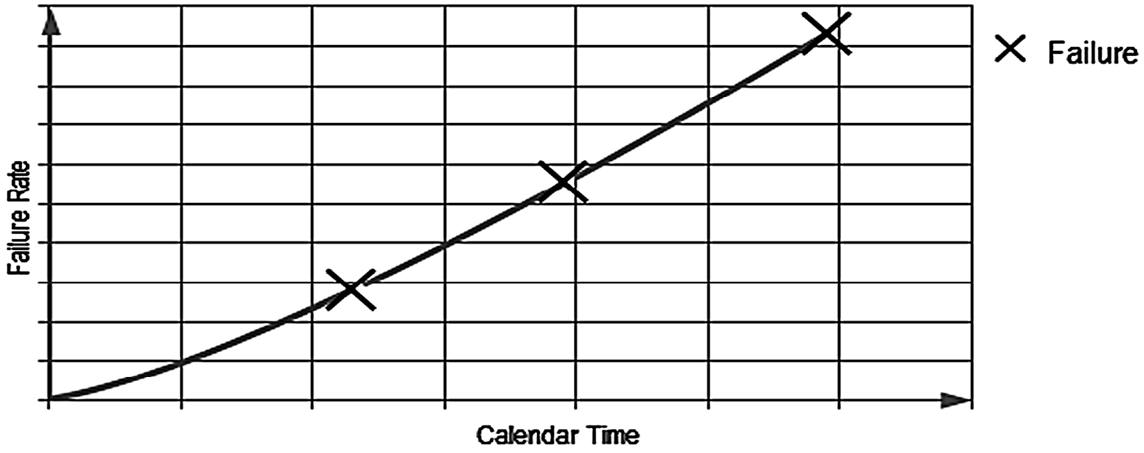
In the case of NHPP, the functions of the reliability and failure probability are expressed according to Figure 3.

Having as a base the former graphic, let's consider that one equipment has a failure in a t_1 time. After being repaired, the functioning is restarted and begins to work in that same point. Then, the reliability function from t_1, for a t time that represents the elapsed time beyond t_1, will be gives as:

$$R(t \mid t > t_1) = \frac{R(t)}{R(t_1)} = 1 - F(t \mid t > t_1)$$

This is called by various authors (Bebbington et al., 2009) as "Mission Time", where t corresponds

Figure 2. Failure rate $\lambda(t)$ in NHPP model



to elapsed calendar time. For a Weibull distribution, from the previous equation, is obtained:

$$R(t_i) = e^{-\left(\frac{t_i}{\alpha}\right)^{\beta}} \quad \wedge \quad R(t_{i-1}) = e^{-\left(\frac{t_{i-1}}{\alpha}\right)^{\beta}}$$

$$R(t_i \mid t_i > t_{i-1}) = \frac{e^{-\left(\frac{t_i}{\alpha}\right)^{\beta}}}{e^{-\left(\frac{t_{i-1}}{\alpha}\right)^{\beta}}} = 1 - F(t_i \mid t_i > t_{i-1})$$

$$\Rightarrow F(t_i \mid t_i > t_{i-1}) =$$

$$1 - \exp\left\{\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right\}$$

where t_{i-1} corresponds to the *total time* elapsed until the last failure and t_i the total time (calendar) elapsed after generate the failure i-th. From this is possible to conclude the following pdf:

$$f(t_i \mid t_i > t_{i-1}) =$$

$$\frac{\beta}{\alpha}\left(\frac{t_i}{\alpha}\right)^{\beta-1} \exp\left\{\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right\}$$

Parameterising of the NHPP Model

In order to obtain the parameters $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, the lineal regression is not a choice. It is ideally made an adjustment by maximum likelihood.

$$P(x_i \text{ en } [\mathrm{x_i},\ \mathrm{x_i}+\mathrm{dx}]\ \forall \mathrm{i} \in \{1,..,\mathrm{n}\}) = \prod_{i=1}^{n} f(x_i;\theta)$$

$$L(\theta) = \prod_{i=1}^{n} f(x_i;\theta)$$

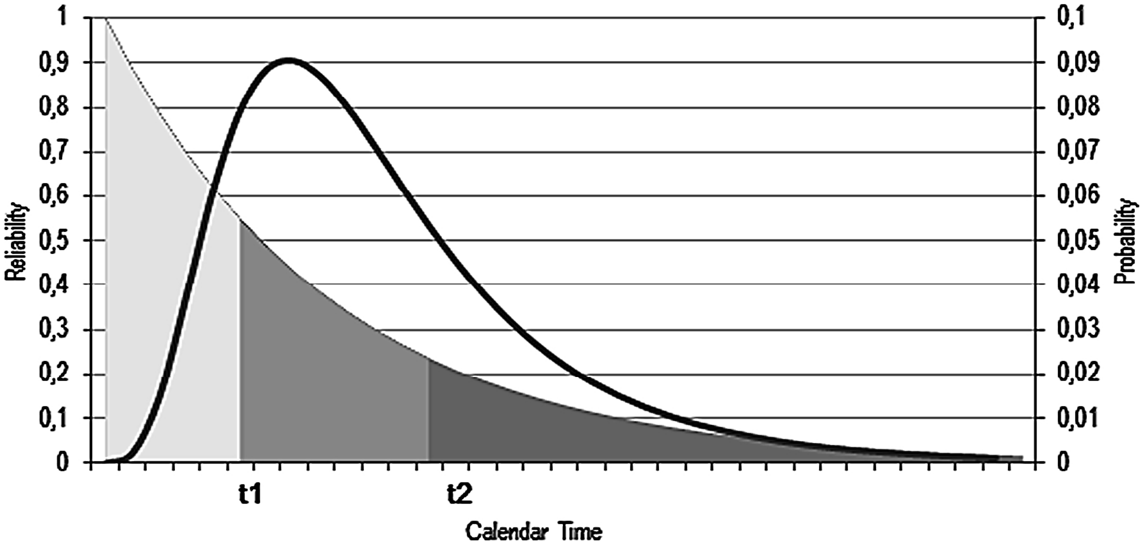
where Θ correspond to the vector of the parameters of distribution to which obey the ***f (t)***. Moreover x_i corresponds to the element i-th of the sample. As it is wished to obtain maximum likelihood between the data and one pdf: ***f (t;Θ)***, the values of the vector Θ are adjusted with the aim to reach that maximum.

Conceptually, parameters are searched in order to better fit to a sample $x_i, \ldots, x_n$ in such way that the probability of the series of values that be presented in a random sample be maximal:

P (x_i en [x_i, x_i, + dx] $\forall$ I $\in$ {1,..,n})

The parameters Θ that give maximum likelihood are those which fulfil with:

Figure 3. R(t) and f(t) on NHPP



$$\frac{\partial L}{\partial \theta} = 0, \qquad i = 1, 2, \ldots m$$

In this way, for the actual case, the likelihood function is shown in Box 4.

Simplifying (Box 5).

After applying partial derivatives and equal to 0, the result of the approaches for NHPP are the following:

$$\overset{\wedge}{\alpha} = \frac{t_n}{n^{1/\beta}}$$

$$\overset{\wedge}{\beta} = \frac{n-1}{\sum_{i=1}^{n-1} \ln\left(\frac{t_n}{t_i}\right)}$$

where t_i corresponds to the elapsed time until the failure i-th and t_n the elapsed time until the last failure.

Simulation for NHPP Model

The lifetime simulation for the equipment modelled by NHPP, having the Weibull case as a base, will be as follows:

Box 4.

$$L = \underbrace{\left[\frac{\beta}{\alpha}\left(\frac{t_1}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t_i}{\alpha}\right)^{\beta}}\right]}_{f(t_1)} \cdot \left[\prod_{i=2}^{n}\left\{\left(\frac{\beta}{\alpha}\right)\left(\frac{t_i}{\alpha}\right)^{\beta-1} e^{\left(\left[\frac{t_{i-1}}{\alpha}\right]^{\beta} - \left[\frac{t_i}{\alpha}\right]^{\beta}\right)}\right\}\right]$$

Box 5.

$$L = \underbrace{\left[\frac{\beta}{\alpha}\left(\frac{t_1}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t_i}{\alpha}\right)^{\beta}}\right]}_{f(t_1)} \cdot \left[\left(\frac{\beta}{\alpha}\right)^{n-1} \prod_{i=2}^{n}\left\{\left(\frac{t_i}{\alpha}\right)^{\beta-1} e^{\left(\left[\frac{t_{i-1}}{\alpha}\right]^{\beta}-\left[\frac{t_i}{\alpha}\right]^{\beta}\right)}\right\}\right]$$

$$\rightarrow L = \underbrace{\left[\frac{\beta}{\alpha}\left(\frac{t_1}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t_i}{\alpha}\right)^{\beta}}\right]}_{f(t_1)} \cdot \left[\left(\frac{\beta}{\alpha}\right)^{n-1} e^{\sum_{i=2}^{n}\left(\left[\frac{t_{i-1}}{\alpha}\right]^{\beta}-\left[\frac{t_i}{\alpha}\right]^{\beta}\right)} \prod_{i=2}^{n}\left[\left(\frac{t_i}{\alpha}\right)^{\beta-1}\right]\right]$$

$$F(t_i) = 1 - \exp\left\{\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right\}$$

$$F(t_i) = u \in U[0,1]$$

$$1 - \exp\left\{\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right\} = u$$

$$\exp\left\{\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right\} = 1 - u$$

$$\ln\left(\exp\left\{\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}\right\}\right) = \ln(1-u)$$

$$\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta} = \ln(1-u)$$

$$\left(\frac{t_i}{\alpha}\right)^{\beta} = \left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \ln(1-u)$$

$$\frac{t_i}{\alpha} = \left(\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \ln(1-u)\right)^{1/\beta}$$

$$t_i = \alpha\left(\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \ln(1-u)\right)^{1/\beta}$$

$$t_i = \left(\alpha^{\beta}\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \alpha^{\beta}\cdot\ln(1-u)\right)^{1/\beta}$$

$$\boxed{t_i = \left(\left(t_{i-1}\right)^{\beta} - \alpha^{\beta}\cdot\ln(1-u)\right)^{1/\beta} \wedge u \in U[0,1]}$$

In this case, t_i, is the total elapsed time, so the time between failures will be expressed as:

$$TBF_i = t_i - t_{i-1}$$

$$\boxed{TBF_i = \left(t_{i-1}{}^{\beta} - \alpha^{\beta}\cdot\ln(1-u)\right)^{1/\beta} - t_{i-1}}$$

Like for PRP, it is here suggested a previous tendency test, commonly developed in order to identify if the equipment has or not modelled behaviour by NHPP.

Numeric Exemplification: NHPP Case

The numeric case corresponds to the analysis of a pulp pump 2(P2). According to, Table 2 contains the time between failures records.

Then, in order to develop the respective adjustment of probability distribution, it is developed step by step:

Step 1: Tendency Test

According to the information shown in Table 2, for the pump 2 it has been recorded 30 times between failures, in hours and in occurrence order.

Again, it is necessary to develop a tendency test, where (as in the previous case) it has been chose the Laplace tendency test, which gives as a result a statistician *z* that must be compared with the standard normal distribution, as it approaches to a random variable. The statistician z is calculated according to:

$$z = \frac{\frac{\sum_{i=1}^{n} t_i}{n} - \frac{t_o}{2}}{t_o\sqrt{\frac{1}{12n}}}$$

t_o: Total accumulated time,
n: Number of times,
t_i: Total accumulated time until element i.

This model is strictly valid for n>3.

$Z = 0$; there is no tendency

> 0; increasing tendency

< 0; decreasing tendency

Evaluating the previous expression we obtain a value $z = 3.3559$. From the standard normal distribution, considering a significance level equal to 0.10, the critical value is equal to 1.645. If $-1.645 < z < 1.645$ then is failed when refusing the hypothesis that there is no tendency. Therefore, having a value z equal to 3.3559 is possible to say that there is tendency in the data, therefore, it is applicable the NHPP model.

Step 2. Distribution Adjustment

Once the NHPP model is justified appropriately (there is tendency), we proceed to apply the distribution adjustment under two-parameter Weibull distribution.

According to maximum likelihood method previously shown, the values of the parameters Θ now $\{\alpha, \beta\}$ that give the maximum likelihood are those which satisfy the following equations already shown:

$$\hat{\beta} = \frac{n-1}{\sum_{i=1}^{n-1} \ln\left(\frac{t_n}{t_i}\right)}$$

Solving the equations through the software RelPro® we have that the parameters are $\alpha = 632.04$, $\beta = 1.99$ respectively.

2.3 Generalized Renewal Process

The traditional models already shown are only able to model 2 types of maintenance: the completely perfect and the completely imperfect. GRP model is the generalization for any level of perfection that has the maintenance, including the both mentioned.

GRP adds a new parameter, called "virtual age". The parameter A_n represents the age of the system at the immediate instant when the n-th repair is carried out. In this way, if $A_n = y$, the element has a time of functioning associated to a probability distribution conditioned for this age y. That is to say, all the failure times have different probability distributions as the time passes by.

Graphically, Figure 4 represents the change of failure rate after each failure.

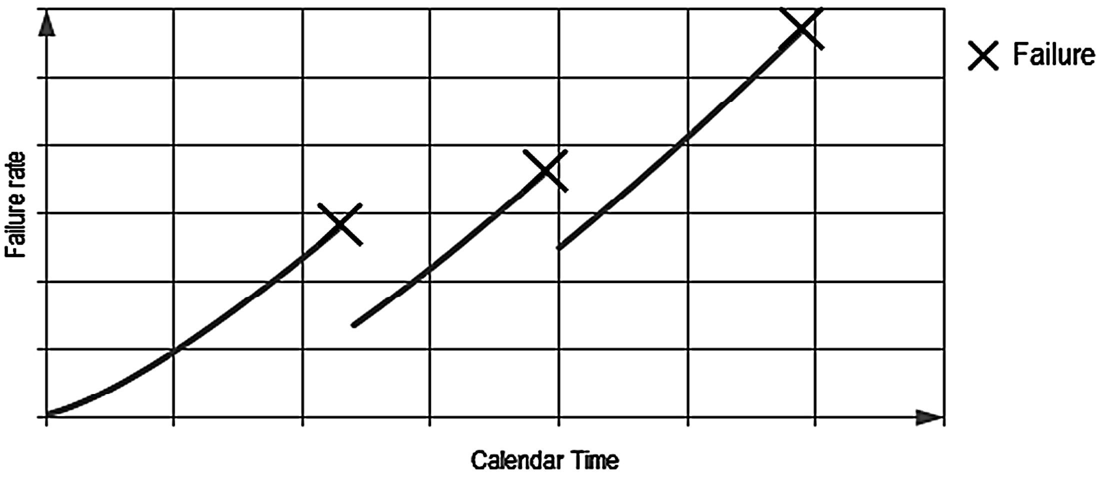
The way to incorporate this variable is considering that equipment begins to operate with certain waste, which is reflected in the reliability function. In this manner, the accumulated reliability and probability distribution for t_{n+1} is:

$$F(t \mid A_n = y) = \frac{F(t+y) - F(y)}{1 - F(y)}$$

$$R(t \mid A_n = y) = \frac{R(t+y)}{R(t)}$$

By this way, it is clear that this "virtual age" is the age of waste in which the equipment begins to work again. The reliability function remains similar to the "Mission Time" only that this does

Figure 4. Failure rate on GRP



not correspond to a real time elapsed, but to an equivalent.

Be x the i-th time of good functioning and T_n the total accumulated time elapsed until failure n-th. As follow:

$$T_n = \sum_{i=1}^{n} x_i \quad (1)$$

On the other hand, the parameter A_n is given by:

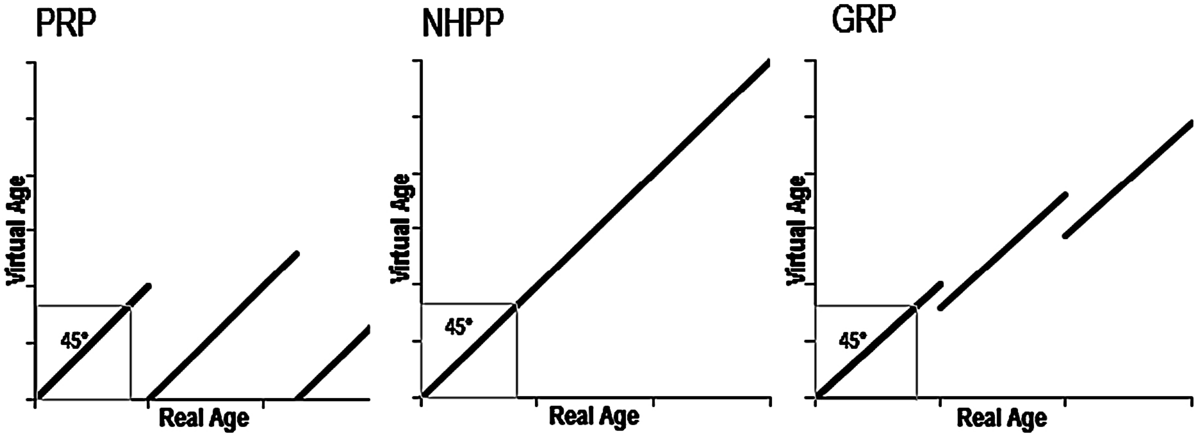
$$A_n = A_{n-1} + q \cdot x_n \quad (2)$$

Using (1) remains that:

$$A_n = qT_n = q\sum_{i=1}^{n} x_i \quad (3)$$

where q is the parameter that decides the ineffectiveness of the repair, in this way q=0 implies that A_n =0, that is to say virtual age equal to 0. Therefore q=0 correspond to a perfect repair case, that is to say is completely effective. In the case it was q=1 then it begins to operate in the same

Figure 5. Real age against virtual age on PRP, NHPP, and GRP



Box 6. Likelihood function

$$L = \underbrace{\left[\frac{\beta}{\alpha} \left(\frac{t_1}{\alpha} \right)^{\beta-1} e^{-\left(\frac{t_1}{\alpha} \right)^{\beta}} \right]}_{f(t_1)} \cdot \left[\prod_{i=2}^{n} \left\{ \left(\frac{\beta}{\alpha} \right) \left(\frac{t_i}{\alpha} \right)^{\beta-1} \exp\left(\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} - \left(\frac{t_i}{\alpha} \right)^{\beta} \right) \right\} \right]$$

part of the reliability function where the equipment failed. This would be:

$0 < q < 1$: GRP
$q = 0$: PRP (HPP)
$q = 1$: NHPP

Plotting the existing relation between real life and virtual age that evolves, it is possible to generate a comparative graphic for PRP, NHPP and GRP. Details in Figure 5.

As in NHPP, it is determined the conditioned reliability and the respective pdf.

$$R(t_i \mid t_i > q \cdot t_{i-1}) = e^{\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} - \left(\frac{t_i}{\alpha} \right)^{\beta}}$$

$$F(t_i \mid t_i > q \cdot t_{i-1}) = 1 - e^{\left(\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} - \left(\frac{t_i}{\alpha} \right)^{\beta} \right)}$$

$$f(t_i \mid t_i > q \cdot t_{i-1}) = \frac{\beta}{\alpha} \left(\frac{t_i}{\alpha} \right)^{\beta-1} e^{\left(\left(\frac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} - \left(\frac{t_i}{\alpha} \right)^{\beta} \right)}$$

Box 7.

$$\frac{\beta}{\alpha^{\beta+1}} \left[\sum_{i=2}^{n} \left[\left(t_i + t_{i-1}(q-1) \right)^{\beta} - \left(q \cdot t_{i-1} \right)^{\beta} \right] \right] + \frac{\beta}{\alpha} \left[\left(\frac{t_1}{\alpha} \right) - (n) \right] = 0 \quad (1)$$

$$\left[\frac{(n)}{\beta} + \ln(t_1) - (n)\ln(\alpha) - \left(\frac{t_1}{\alpha} \right)^{\beta} \ln\left(\frac{t_1}{\alpha} \right) \right] +$$
$$\sum_{i=2}^{n} \left[\begin{matrix} \ln\left(t_i + t_{i-1}(q-1) \right) - \left(\dfrac{t_i + t_{i-1}(q-1)}{\alpha} \right)^{\beta} \\ \ln\left(\dfrac{t_i + t_{i-1}(q-1)}{\alpha} \right) + \left(\dfrac{q \cdot t_{i-1}}{\alpha} \right)^{\beta} \ln\left(\dfrac{q \cdot t_{i-1}}{\alpha} \right) \end{matrix} \right] = 0 \quad (2)$$

$$(\beta - 1) \sum_{i=2}^{n} \left[\frac{t_{i-1}}{t_i + t_{i-1}(q-1)} \right] + \frac{\beta q^{(\beta-1)}}{\alpha^{\beta}} \sum_{i=2}^{n} \left(t_{i-1} \right)^{\beta} -$$
$$\frac{\beta}{\alpha^{\beta}} \sum_{i=2}^{n} \left(t_i + t_{i-1}(q-1) \right)^{\beta-1} \left(t_{i-1} \right) = 0 \quad (3)$$

Box 8.

$$\frac{\beta}{\alpha^{\beta+1}}\left[\sum_{i=2}^{n}\left[X_i^{\beta}-Y_i^{\beta}\right]\right]+\frac{\beta}{\alpha}\left[\left(\frac{t_1}{\alpha}\right)-(n)\right]=0 \quad (1)$$

$$\left[\frac{(n)}{\beta}+\ln(t_1)-(n)\ln(\alpha)-\left(\frac{t_1}{\alpha}\right)^{\beta}\ln\left(\frac{t_1}{\alpha}\right)\right]+$$
$$\sum_{i=2}^{n}\left[\ln\left(X_i\right)-\left(\frac{X_i}{\alpha}\right)^{\beta}\ln\left(\frac{X_i}{\alpha}\right)+\left(\frac{Y_i}{\alpha}\right)^{\beta}\ln\left(\frac{Y_i}{\alpha}\right)\right]=0 \quad (2)$$

$$(\beta-1)\sum_{i=2}^{n}\left[\frac{t_{i-1}}{X_i}\right]+\frac{\beta q^{(\beta-1)}}{\alpha^{\beta}}\sum_{i=2}^{n}\left(t_{i-1}\right)^{\beta}-\frac{\beta}{\alpha^{\beta}}\sum_{i=2}^{n}\left(X_i\right)^{\beta-1}\left(t_{i-1}\right)=0 \quad (3)$$

Parameterising of the GRP Model

The adjustment developed is on the basis of a pdf with two-parameter Weibull (α, β), and adding the parameter q, so then we have 3 parameters to determine. The most common approach for parameters corresponds by maximum likelihood to the following expression (Box 6).

With the partial derivative in each variable, it is obtained a set of 3 equations with 3 unknown quantities, these are: α, β, q.

Then, there is a set of 3 equations, which are:

$$\frac{\partial[\ln(L)]}{\partial\alpha}=0,\frac{\partial[\ln(L)]}{\partial\beta}=0,\frac{\partial[\ln(L)]}{\partial q}=0$$

Developing each partial derivative, there is (Box 7).

Generalizing the main expressions, there is (Box 8).where: $X_i = t_i + t_{i-1}(q - 1) \wedge Y_i = q \cdot t_{i-1}$

The parameters, α, β, q are the 3 values to identify. Searching these parameters is a very exhaustive procedure, as it requires more precision in the procedure, generally is a long process, so it is suggested to use the Monte Carlo simulation.

The searching of α, β, q starts with the simulation of *q* and β, repeated by even distributions.

$$q \in U[0,1]$$
$$\beta \in U[0,10]$$

The parameter q only can be between 0 and 1 and the parameter β hardly exceed the value 10 (Yañez et al., 2002). On the other hand, the value of α has a wide rank of possibilities that is why it is used the third equation of the system which allows expressing α from *q* and β. Similar to approach *a* for GRP Model remains:

$$\overset{\wedge}{\alpha}=\sqrt[\beta]{\frac{\sum_{i=2}^{n}\left[\left(t_i+t_{i-1}(q-1)\right)^{\beta}-\left(q\cdot t_{i-1}\right)^{\beta}\right]+t_1^{\beta}}{n}}$$

Then the values of α, β, q are given by those 3 values that satisfy in a better way the first 2 equations of the set. (The third one is obviated since it is used to obtain *a).*

Figure 6. Diagram process for GRP adjustment

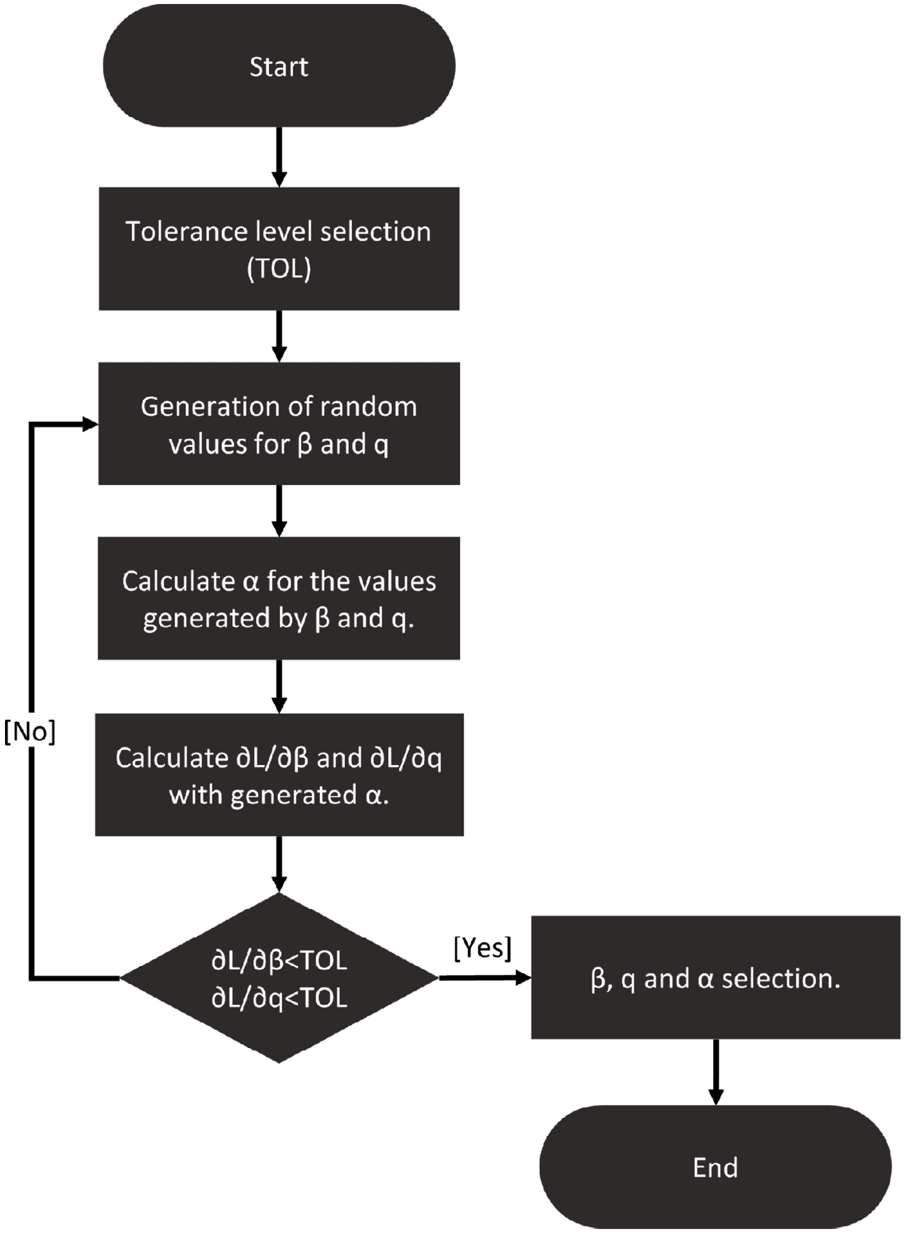


Figure 6 represents the procedure for the GRP adjustment.

As far as the probability to find the values that grant the global maximum of the maximum likelihood function is virtually invalid through random search, it is necessary to define a value of tolerance for the partial derivatives ($\partial L/\partial B$ and $\partial L/\partial q$) equal to 0, being necessary to fix this value of tolerance "TOL" as an acceptable rank to consider that is found in a global maximum and in this way to accept the respective distribution adjustment.

Considering the adding of a new parameter, in this case q, always the adjustment GRP will give a higher likelihood than a PRP or NHPP adjustment. Nevertheless, in order to consider the existence and applicability of these cases, it is necessary to count on selection criteria. This is applied after the adjustment through GRP once obtained the parameter q.

As q value is always a continuous value, the probability to be exactly q=1 or q=0 is practically null, therefore it is considered a new tolerance level, which has been called TQ.

This tolerance level corresponds to higher and lower percentage of the possibilities that value q has.

This goal of this value is to identify when would be more appropriate to consider a PRP or NHPP model. Therefore the practical expression corresponds to:

Box 9.

$$F(t_i)=1-\exp\left\{\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\left(\frac{t_i}{\alpha}\right)^{\beta}\right\}\wedge F(t_i)=u\in U[0,1]$$

$$1-\exp\left\{\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\left(\frac{t_i}{\alpha}\right)^{\beta}\right\}=u$$

$$\exp\left\{\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\left(\frac{t_i}{\alpha}\right)^{\beta}\right\}=1-u$$

$$\ln\left(\exp\left\{\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\left(\frac{t_i}{\alpha}\right)^{\beta}\right\}\right)=\ln(1-u)$$

$$\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\left(\frac{t_i}{\alpha}\right)^{\beta}=\ln(1-u)$$

$$\left(\frac{t_i}{\alpha}\right)^{\beta}=\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\ln(1-u)$$

$$\frac{t_i}{\alpha}=\left(\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\ln(1-u)\right)^{1/\beta}$$

$$t_i=\alpha\left(\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\ln(1-u)\right)^{1/\beta}$$

$$t_i=\left(\alpha^{\beta}\left(\frac{q\cdot t_{i-1}}{\alpha}\right)^{\beta}-\alpha^{\beta}\cdot\ln(1-u)\right)^{1/\beta}$$

$$\boxed{t_i=\left(\left(q\cdot t_{i-1}\right)^{\beta}-\alpha^{\beta}\cdot\ln(1-u)\right)^{1/\beta}\wedge u\in U[0,1]}$$

$$\begin{array}{ll} 0+TQ<q<1-TQ & : \text{GRP} \\ q=<TQ & : \text{PRP} \\ q>=1-TQ & : \text{NHPP} \end{array}$$

Simulation for GRP Model

For the simulation, the case is very similar to NHPP Model, due to fact that it is originated from the function of density of conditional probability that the equipment has survived until a given **t** time.

Considering (Box 9):

Then, as t_i corresponds to the total time elapsed, a simulated TBF value will be depicted by:

$$TBF_i = t_i - t_{i-1}$$

$$\boxed{TBF_i = \left(\left(q \cdot t_{i-1}\right)^{\beta} - \alpha^{\beta} \cdot \ln(1-u)\right)^{1/\beta} - q \cdot t_{i-1}}$$

Numeric Exemplification: GRP Case

The numeric case corresponds to the analysis of a pulp pump 3 (P3). According to, Table 3 contains the time between failures records.

Therefore, in order to develop the respective adjustment of probability distribution, it is developed step by step:

Step 1: Tolerance Level

The tolerance level is defined for the partial derivatives as TOL= 0.01 and tolerance for *q* value is TQ=5%

Step 2: Distribution Adjustment

Once defined the tolerance level for GRP adjustment it is proceed with respective adjustment.

Solving the equations through RelPro software, the parameters are:

α=1986.067; β= 2.026 and q =0.192

With these parameters we obtain:

$$\left|\frac{\partial[\ln(L)]}{\partial\beta}\right| = 1,76\times10^{-7} < TOL = 0,01$$

$$\left|\frac{\partial[\ln(L)]}{\partial q}\right| = 0,009833 < TOL = 0,01$$

Therefore, the distribution adjustment is suitable, due to fact that the tolerance level in the random search is completely appropriately.

Regarding *q* value there is**:**

$$TQ = 0,05 < q = 0,192 < 1 - TQ = 0,95$$

Therefore, when we find an adjustment solution by maximum likelihood with acceptable derivatives that guarantee the quality of the adjustment and a *q* parameter with a numeric value between the rank 0.05<q<0.95, it is possible to affirm that the use of GRP model is suitable for the case.

3. CONCLUSION

The reliability model is an essential aspect for the management and optimization of physical industrial assets. The wide range and variability of their behaviour, demands the application of techniques of diverse complexity and depth, that allow adapting in a better way to each one of the realities.

The variable that defines and determines the use of the techniques is the state in which remains the assets after a repair. In this sense, the repair classifications are five: perfect, minimum, imperfect, over-perfect and destructive.

For a perfect maintenance, it is used and recommended the Perfect Renewal Process PRP through the Homogeneous Poisson Process HPP. In the case of a minimum repair, generally is depicted through Non-Homogeneous Poisson Process NHPP being the most used model the "Power Law".

In spite of the large application of the previous models, there are varied situations that are not covered due to the fact that the generality of the repair cases are between the perfect and the minimum. For these situations, it is headed and developed the "Generalized Renewal Process" GRP. Given the flexible structure that the GRP model has, that allows adapting to the different kinds of maintenance, its development is quite complicated; due to the partial incorporation of the parameter virtual age An and the weighting factor q. Moreover, as the probability to find values that grant the global maximum of the maximum plausibility function is practically null, through the random search, it is necessary to define a tolerance value for the partial derivatives ($\partial L/\partial \beta$ and $\partial L/\partial q$), that are equal to cero, establishing this tolerance value "TOL" as an acceptable rank to consider the distribution adjustment. It is for this reason that the simulation techniques (especially Monte Carlo simulation), arise as powerful alternatives for its resolution.

In order to learn in detail the step by step of each model is a fundamental task to apply effective and correctly each model. Diverse researches omit the process of resolution and only present final results indicating the use of a model and the use of some computed tool with integrated algorithm. It was showed in different researches, which motivated the research team to develop a specific conceptual pattern and resolution practical for each stochastic parametric model former mentioned. This is fundamental to recognize the value of this work and its contribution for future researchers who wish to learn and apply this knowledge. For this reason, this research becomes an analytic and explicative procedure about the definition, calculation methodology and criteria that must be considered to parameterise industrial assets under certain degradation level after maintenance, complementing in addition its analysis with a numeric application that allows demonstrating step by step the mathematic and stochastic development as appropriate. The practical cases chosen were developed in the mining industry of Chile.

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KEY TERMS AND DEFINITIONS

Failure Rate: Is the rate of failure occurrence per units of time, distance, cycles or other measure. Degradation Level: Effects of the wearing down over a determined element, given by: time, conditions of use, among other factors.

Imperfect Maintenance: Maintenance action where the intervened item is restored to a condition "worse than new but better than old".

Non Repairable System: A system that cannot be restored to an operational status after a failure, and have to be replaced to return the functionality.

Parameterization: Defining the parameters necessary to model or represent a specific variable.

Repairable System: A system that can be restored to an operational status after a failure.

Tolerance Level: Corresponds to a maximum value (near to zero) for differential equations that maximize a certain likelihood function, in which can be assumed that has been found an optimal solution.

APPENDIX: NOTATIONS

PRP: Perfect Renewal Process.
NHPP: Non-Homogeneous Poisson Process.
GRP: Generalized Renewal Process.
L(*t*): Failure Rate of an element in a given time t.
Ti: Function time between failure i-1 and i-th.
***F(t)*:** Probability density function of failure (pdf) of an element with operation time *t.*
F(t): Probability density function of accumulated failure of an element with operation time *t.*
G(t): Gamma function.
F(t;Θ): Probability density function of failure of an element with operation time *t*, with forma and scale parameters given by vector 0.
L(Θ): Likelihood function for parameters vector 0 in a pdf given.
MTTF: Mean time to failure.
MTTR: Mean time to repair.
â: Estimated value of the parameter *a* (applicable for all parameters).
A_n.: Virtual age of system at the immediate moment of the repair of n-th.
T_n: Virtual age (of operation) at the immediate moment of the repair of n-th.
q: Parameter which establishes the defect of the repair.
TOL: Numeric grade to consider acceptable a distribution adjustment through the likelihood maximum.
TQ: Tolerance that corresponds to higher or lower percentage of the possibilities of value q.

2. INFORME DE LA RELEVANCIA CIENTÍFICA DE LAS PUBLICACIONES

INFORME DE LA RELEVANCIA CIENTÍFICA DE LAS PUBLICACIONES

1. Viveros Gunckel, P., Crespo Márquez, A., Barberá Martinez, L., and Gonzalez Rossel, J. P. (2016) Graphical Analysis for Operation Management: A Graphical Method to Support Operation Decision Making. Qual. Reliab. Engng. Int., 32: 2299–2311. DOI: 10.1002/qre.1936

Quality and Reliability Engineering International

Impact Factor: 1.457 (2015); 1.533 (5 años)

Categoría de JCR ®	**Clasificación en la categoría**	**Cuartil en la categoría**
ENGINEERING, MULTIDISCIPLINARY	28 de 85	Q2
ENGINEERING, INDUSTRIAL	21 de 44	Q2

JCR	**ENGINEERING, MULTIDISCIPLINARY**			**ENGINEERING, INDUSTRIAL**		
Year	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile
2015	28/85	Q2	67.647	21/44	Q2	53.409
2014	33/85	Q2	61.765	22/43	Q3	50.000
2013	41/87	Q2	53.448	26/43	Q3	40.698
2012	47/90	Q3	48.333	30/44	Q3	32.955
2011	46/90	Q3	49.444	27/43	Q3	38.372
2010	53/87	Q3	39.655	31/38	Q4	19.737

Fuente: Web of Knowledge. Thomson Reuters.

2. Viveros-Gunckel, P., Crespo-Marquez, A., Tapia, R., Kristjanpoller-Rodriguez, F., Gonzalez-Prida-Diaz, V. (2016). RELIABILITY STOCHASTIC MODELING FOR REPAIRABLE PHYSICAL ASSETS. CASE STUDY APPLIED TO THE CHILEAN MINING. DYNA, 91(4). 423-431. DOI: http://dx.doi.org/10.6036/7863

DYNA

Impact Factor: 0.302 (2015); 0.234 (5 años)

Categoría de JCR ®	**Clasificación en la categoría**	**Cuartil en la categoría**
ENGINEERING, MULTIDISCIPLINARY	77 de 85	Q4

JCR	**ENGINEERING, MULTIDISCIPLINARY**		
Year	Rank	Quartile	JIF Percentile
2015	77/85	Q4	10.000
2014	84/85	Q4	1.765
2013	82/87	Q4	6.322
2012	81/90	Q4	10.556
2011	84/90	Q4	7.222
2010	76/87	Q4	13.218

Fuente: Web of Knowledge. Thomson Reuters.

3. Gunckel, Pablo A. Viveros, Adolfo Crespo Márquez, Fredy A. Kristjanpoller, Rene W. Tapia and Vicente González-Prida. "Mathematical and Stochastic Models for Reliability in Repairable Industrial Physical Assets." Promoting Sustainable Practices through Energy Engineering and Asset Management. IGI Global, 2015. 287-310. Web. 16 Jan. 2017. DOI: 10.4018/978-1-4666-8222-1.ch012.

https://www.elsevier.com/__data/assets/excel_doc/0016/91123/Scopus_books_01_03_16.xlsx.

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January, 2017

I am pleased to recognize the books edited by Dr. Vicente Gonzalez-Prida published by IGI Global.

- González-Prida, V., & Raman, A. (2015). Promoting Sustainable Practices through Energy Engineering and Asset Management (pp. 1-402). Hershey, PA: IGI Global. doi:10.4018/978-1-4666-8222-1. http://www.igi-global.com/book/promoting-sustainable-practices-through-energy/121160. Release date: March 2015.

- Carnero, M. C., & González-Prida, V. (2017). Optimum Decision Making in Asset Management (pp. 1-523). Hershey, PA: IGI Global. doi:10.4018/978-1-5225-0651-5. http://www.igi-global.com/book/optimum-decision-making-asset-management/147734. Release date: August 2016.

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Sincerely,

Jan Travers

Jan Travers
Director of Intellectual Property and Contracts

701 E. Chocolate Avenue,• Hershey PA 17033-1240, USA• Tel: 717/533-8845 • Fax: 717/533-8661 • E-mail: cust@igi-global.com • www.igi-global..com

3. ACEPTACIÓN DE LOS COAUTORES DE LA PRESENTACIÓN DE LOS TRABAJOS COMO TESIS

Aceptación de la presentación de trabajos como tesis

Yo, **Juan Pablo González Rossel**, Ingeniero Civil Industrial de la Universidad Técnica Federico Santa María, declaro mi aceptación a la presentación del siguiente trabajo como parte del trabajo de Tesis de **Pablo Viveros Gunckel** en el Programa de Doctorado en Ingeniería Mecánica y de Organización Industrial de la Universidad de Sevilla.

Trabajo:

- Viveros Gunckel, P., Crespo Márquez, A., Barberá Martinez, L., and Gonzalez Rossel, J. P. (2016) Graphical Analysis for Operation Management: A Graphical Method to Support Operation Decision Making. Qual. Reliab. Engng. Int., 32: 2299–2311. doi: 10.1002/qre.1936.

Juan Pablo González Rossel

Valparaíso, 20 de diciembre de 2016

Aceptación de la presentación de trabajos como tesis

Yo, **Luis Barberá Martinez**, Doctor de la Universidad de Sevilla, declaro mi aceptación a la presentación del siguiente trabajo como parte del trabajo de Tesis de **Pablo Viveros Gunckel** en el Programa de Doctorado en Ingeniería Mecánica y de Organización Industrial de la Universidad de Sevilla

Trabajos:

- Viveros Gunckel, P., Crespo Márquez, A., Barberá Martinez, L., and Gonzalez Rossel, J. P. (2016) Graphical Analysis for Operation Management: A Graphical Method to Support Operation Decision Making. Qual. Reliab. Engng. Int., 32: 2299–2311. doi: 10.1002/qre.1936.

Luis Barberá Martinez

Valparaíso, 20 de diciembre de 2016

Aceptación de la presentación de trabajos como tesis

Yo, **René Tapia Peñaloza**, Ingeniero Civil Industrial de la Universidad Técnica Federico Santa María, declaro mi aceptación a la presentación de los siguientes trabajos como parte del trabajo de Tesis de **Pablo Viveros Gunckel** en el Programa de Doctorado en Ingeniería Mecánica y de Organización Industrial de la Universidad de Sevilla.

Trabajos:

- Viveros P, Crespo A, Tapia R, Kristjanpoller F, González-Prida V. Reliability stochastic modeling for repairable physical assets. Case study applied to the Chilean mining. DYNA. Volume 91. Pages: 423-431, Julio-Agosto 2016. DOI: 10.6036/7863.
- Pablo Viveros, Fredy Kristjanpoller, Adolfo Crespo, René Tapia & Vicente González-Prida. "Mathematical and Stochastic Models for Reliability in Repairable Industrial Physical Assets". Chapter 12. Practices through Energy Engineering and Asset Management. Engineering Science Reference (an imprint of IGI Global). USA, 2015.

René Tapia Peñaloza

Valparaíso, 20 de diciembre de 2016

Aceptación de la presentación de trabajos como tesis

Yo, **Vicente González-Prida**, Doctor de la Universidad de Sevilla, declaro mi aceptación a la presentación de los siguientes trabajos como parte del trabajo de Tesis de **Pablo Viveros Gunckel** en el Programa de Doctorado en Ingeniería Mecánica y de Organización Industrial de la Universidad de Sevilla.

Trabajos:

- Viveros P, Crespo A, Tapia R, Kristjanpoller F, González-Prida V. Reliability stochastic modeling for repairable physical assets. Case study applied to the Chilean mining. DYNA. Volume 91. Pages: 423-431, Julio-Agosto 2016. DOI: 10.6036/7863.
- Pablo Viveros, Fredy Kristjanpoller, Adolfo Crespo, René Tapia & Vicente González-Prida. "Mathematical and Stochastic Models for Reliability in Repairable Industrial Physical Assets". Chapter 12. Practices through Energy Engineering and Asset Management. Engineering Science Reference (an imprint of IGI Global). USA, 2015.

Vicente Gonzalez-Prida

Valparaíso, 20 de diciembre de 2016

Aceptación de la presentación de trabajos como tesis

Yo, **Fredy Kristjanpoller Rodríguez**, Candidato a Doctor de la Universidad de Sevilla, declaro mi aceptación a la presentación de los siguientes trabajos como parte del trabajo de Tesis de **Pablo Viveros Gunckel** en el Programa de Doctorado en Ingeniería Mecánica y de Organización Industrial de la Universidad de Sevilla.

Trabajos:

- Viveros P, Crespo A, Tapia R, Kristjanpoller F, González-Prida V. Reliability stochastic modeling for repairable physical assets. Case study applied to the Chilean mining. DYNA. Volume 91. Pages: 423-431, Julio-Agosto 2016. DOI: 10.6036/7863.
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Fredy Kristjanpoller Rodríguez

Valparaíso, 20 de diciembre de 2016

3. RENUNCIA DE LAS PERSONAS QUE COMPARTAN AUTORÍA QUE NO SEAN DOCTORES A PRESENTARLOS COMO PARTE DE OTRA TESIS

Renuncia de las personas que compartan autoría que no sean doctores a presentarlos como parte de otra tesis

Yo **Fredy Kristjanpoller Rodríguez**, Candidato a Doctor de la Universidad de Sevilla, declaro mi renuncia a presentar los siguientes artículos como parte de mi tesis doctoral, aceptando la presentación de los mismos como parte del trabajo de Tesis de **Pablo Viveros Gunckel** en el Programa de Doctorado en Ingeniería Mecánica y de Organización Industrial de la Universidad de Sevilla

Trabajos:

- Viveros P, Crespo A, Tapia R, Kristjanpoller F, González-Prida V. Reliability stochastic modeling for repairable physical assets. Case study applied to the Chilean mining. DYNA. Volume 91. Pages: 423-431, Julio-Agosto 2016. DOI: 10.6036/7863.
- Pablo Viveros, Fredy Kristjanpoller, Adolfo Crespo, René Tapia & Vicente González-Prida. "Mathematical and Stochastic Models for Reliability in Repairable Industrial Physical Assets". Chapter 12. Practices through Energy Engineering and Asset Management. Engineering Science Reference (an imprint of IGI Global). USA, 2015

Fredy Kristjanpoller Rodríguez

Valparaíso, 20 de diciembre de 2016

Renuncia de las personas que compartan autoría que no sean doctores a presentarlos como parte de otra tesis

Yo, **Juan Pablo González Rossel**, Ingeniero Civil Industrial de la Universidad Técnica Federico Santa María, declaro mi renuncia a presentar el siguiente artículo como parte de mi tesis doctoral, aceptando la presentación de los mismos como parte del trabajo de Tesis de **Pablo Viveros Gunckel** en el Programa de Doctorado en Ingeniería Mecánica y de Organización Industrial de la Universidad de Sevilla

Trabajos:

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Juan Pablo González Rossel

Valparaíso, 20 de diciembre de 2016

Renuncia de las personas que compartan autoría que no sean doctores a presentarlos como parte de otra tesis

Yo, **René Tapia Peñaloza**, Ingeniero Civil Industrial de la Universidad Técnica Federico Santa María, declaro mi renuncia a presentar los siguientes artículos como parte de mi tesis doctoral, aceptando la presentación de los mismos como parte del trabajo de Tesis de **Pablo Viveros Gunckel** en el Programa de Doctorado en Ingeniería Mecánica y de Organización Industrial de la Universidad de Sevilla

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René Tapia Peñaloza

Valparaíso, 20 de diciembre de 2016

5. PUBLICACIONES EN CONGRESOS INTERNACIONALES

1. P. Viveros, A. Crespo, F. Kristjanpoller, R. Stegmaier, E. Johns, V. Gonzalez-Prida. Probabilistic Performance Assessment for Crushing System. A Case Study for a Mining Process. In: PSAM14 - Probabilistic Safety Assessment and Management. June 22 – 27, 2014. Honolulu, Hawaii, USA. http://www.scopus.com/inward/record.url?eid=2-s2.0-84925061938&partnerID=40&md5=6efec791abc2282f4919cbe14c39db36

2. P. Viveros, A. Crespo, L. Barberá, F. Kristjanpoller, R. Stegmaier, E. Johns, T. Grubessich. General Framework about Graphical Analysis for Operation Management. The Annual European Safety and Reliability Conference (ESREL). Zurich, Switzerland. Sept 7-10, 2015. DOI: 10.1201/b19094-140

3. P. Viveros, A. Crespo, L. Barberá, F. Kristjanpoller, R. Stegmaier, E. Johns, T. Grubessich. General Framework about Graphical Analysis for Overall Effectiveness Management. The Annual European Safety and Reliability Conference (ESREL). Glasgow, Scotland. Sept 25-29, 2016. CRC Press, 2016ISBN: 149878898X, 9781498788984

Risk, Reliability and Safety: Innovating Theory and Practice – Walls, Revie & Bedford (Eds)

General framework about graphical analysis for overall effectiveness management

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ABSTRACT: This article introduces a general framework about a graphical tool for the monitoring of performance indicators called GAOEM (Graphical Analysis for Overall Effectiveness Management). GAOEM is used in a real industrial process, integrating the main indicators of maintenance and operations management and performing an adaptation on the indicator of the overall effectiveness, the OEE/OAE. GAOEM facilitates control and analysis by using specific indicators (graphic panel). It also facilitates an efficient reading and interpreting of the data, enriching the analysis, the search for phenomena of interest and improvement opportunities and supporting the decision making. GAOEM can be used as a diagnosis, analysis, control and monitoring tool for the indicators of interest, as well as a tool for searching of phenomena typical of the life cycle of assets and also those that result from improper operation and/or maintenance, identifying its root causes.

1 INTRODUCTION

The performance measurement corresponds to the quantification process of an action, where this measurement is the process of quantification and the action leads to a performance [1].

The concepts of efficiency and effectiveness are precisely used in this context, where effectiveness refers to the extent to which the objectives or requirements defined for the process are met, while efficiency is a measure of the economy in which the resources of the company in meeting the targets set are used [2]. It is also known that there is a close relationship between management control through performance indicators, defining strategies and decision making [3, 4].

There are different proposals for the design of measurement and control systems, all of them agree with: defining goals and performance criteria (KPI) [5-7], quality of reporting [8-10], information systems with consolidated [11-13] and purged database [14, 15], and well-established processes for validating results [16]. Currently, from the point of view of tools and methods for the design of control and management systems, it is important to mention: The Balanced Scorecard (BSC) [17, 18], Total Productive Maintenance [19, 20], Overall Equipment Effectiveness (OEE) [21, 22], Total Equipment Effectiveness Performance (TEEP) [23], Production Equipment Effectiveness (PEE) [24], the Overall Asset Efficiency (OAE) or the Total Plant Efficiency (OPE) [21].

The current scenario of competitiveness in the industry calls for further integration of maintenance management to the management of production and its operations, with the ultimate goal of producing at a minimal cost. To achieve these goals, properly designed key performance indicators (KPI) and practical and easy to use tools that allow representing quantitatively the performance of the system are needed.

A common and a fundamental problem in the development and control of production and maintenance plans is achieving the standards and goals planned by the organization, mainly due to the lack of practical mechanisms of information analysis that support decision making. In particular, tools that show patterns of deficiencies related to the use and performance of the equipment in a clear and simple way are needed.

Generally, the lack of information and its quality make difficult to carry out control tests that deliver early warnings in yields and operation of the equipment. Therefore, designing methods of quantitative analysis and graphs that are easy to interpret is even more necessary as they facilitate the decision making by improving the operational performance of the system as a whole.

To achieve the GAOEM goals efficiently and effectively, it is advisable to elaborate a high performance information system at an early stage of the implementation [16, 25, and 27] that allows predefined consultations and analysis. The relationship between the possible sources of information, their processing and the result of a consolidated information system that meets the requirements of GAOEM must elaborated at the beginning of the implementation. Obviously this process must be supervised and supported by the experience and knowledge of the organization and the responsible staff

It is recommended to use advanced systems for the automatic registration and ideally in real time, complementing this with systems of management of notification maintenance and work orders. Through this integration a consolidated database will be achieved, which will be the base information to calculate the basic performance indicators (BPIs) of GAOEM, being these essential for the continuous control and monitoring of the level of performance.

This article presents a graphical tool for the monitoring of performance indicators (GAOEM) for the operation in the mining industry (main industry in Chile), integrating the main indicators of maintenance and operation management, and it presents particularly an adaptation on the indicator of the overall effectiveness of assets, the OEE/OAE. GAOEM facilitates control and analysis by using specific indicators (graphic panel). It also facilitates an efficient reading and interpreting of the data, enriching the analysis, the search for phenomena of interest and improvement opportunities and supporting the decision making.

Some generally required questions, to develop the GAOEM proposal, are presented in Table 1.

Table 1. Some important questions to be answered by the tool.

1. – Are the production targets for the period in analysis being met?
2. – What is the result, at a global performance level, of the areas: Operation y Maintenance?
3. – What is the incidence of each area on the overall efficiency of the process?
4. – What is the trend of the performance of the areas?
5. – What phenomena, understood as hypothesis of primary causes of performance deviation, are evident in the results?

2 GAOEM METHOD

2.1 *Introduction*

The GAOEM method is built from a database related to the production process, namely: intervention data (number of intervention, type of intervention, stop/no stop) time data (cumulated time, duration of intervention) and production data (cumulated production, cumulated defective products, nominal capacity of the asset).

GAOEM allows controlling and diagnosing the overall efficiency of the production equipment, shortening diagnosis and interpretation of historical time data, systematizing the process of identifying potential problems linked to the use of assets and thus increasing the productivity and profitability. The definition of the OEE developed in [22] exposes six loss agents and it organizes them into three integrated approaches of efficiency: Maintenance, Production and Quality. This original proposal excludes the planned interventions (preventive maintenance) from the availability calculation, hence from the overall equipment effectiveness (OEE). For this reason, the conceptual and computational proposal is not applicable in industries with high asset base as in the case of the mining industry in Chile, which demands a more representative adaptation.

In the mining industry context, generating an indicator of overall efficiency for the assets is essential to the comprehensive management of production, involving the maintenance area and the area of operations respectively. GAOEM is built from five indicators, which are defined as:

- Availability [A]: Percentage of total time in which an asset may fulfill the function for which it was intended. Availability does not necessarily mean that the equipment is working but that it is able to work.
- Utilization [U]: Percentage of total time in which the asset is being used for productive purposes, regardless of the production rate.
- Effective Utilization [Ue]: Percentage of the available time in which the asset is being used for productive purposes, regardless the production rate.
- Performance [P]: This index incorporates the efficiency losses due to lower detentions (partial/total), where the production is interrupted due to a machine operating at idle or to an operational requirement (load or production rate) lower or higher than the one established by design in the process.
- Quality [Q]: This index incorporates the efficiency losses that result from deviations in the established quality standards and/or material rework.

$$Availability\ (A) = \frac{Available\ Time}{Total\ Base\ Time}$$

$$Effective\ Utilization\ Rate\ (U^{*}) = \frac{Operating\ Time}{Available\ Time}$$

$$Performance\ (P) = \frac{Equivalent\ Time\ Production}{Operating\ Time}$$

$$Quality\ (Q) = \frac{Effective\ Time\ Production}{Equivalent\ Time\ Production}$$

$$OAE = A\ x\ U^{*} x\ P\ x\ Q$$

Figure 1. Presents the adaptation of the proposal to the case of the mining industry.

Table 2. a: Intervention Information.

Class	Description
N° Intervention **[Ni]**	Assigns the number of occurrence of the intervention ith. It is a natural number under consecutive order
Stop/Do not Stop **[DET i]**	Reports whether the intervention stopped **(0)** or not stopped **(1)** the operation. It is a Binary variable.
Type of Intervention **[CI i]**	Corrective Intervention **(CM)**, associated with the value 1. It is a maintenance action after the occurrence of a failure. **[CI i = 1]** Preventive Intervention **(PM)**, associated with the value 2. It is a maintenance action prior to a failure. **[CI i = 2]** Operational Intervention **(OI)**, associated with the value 3. Do not execute a maintenance action. It generates a detention or reducing capacity performance. **[CI i = 3]**

Table 2. b: Time Information.

Class	Description
Cumulative Calendar Time **[CCT i]**	It is the cumulative time when the ith intervention occurs. Counted from the beginning of the evaluation horizon (T=0)
Time of Intervention **[TI i]**	Time duration requested for the ith intervention. Related to the Time to Repair.

2.2 *Input information*

The input information is necessary for the success of GAOM method. The classification is presented in Tables 2 (2.a; 2.b; 2.c).

Table 2. c: Production Information.

Class	Description
Cumulative Production **[CP i]**	It is the cumulative production when the ith intervention occurs. Counted from the beginning of the evaluation horizon (T=0)
Cumulative defective production **[CDP i]**	It is the cumulative defective production (out of quality standard) when the ith intervention occurs. Counted from the beginning of the evaluation horizon (T=0)
Nominal Production Capacity **[NCP]**	Nominal capacity of the process. It must be settled by operation.

Table 3. Standard format for input data collection.

Intervention data			Production data (Ton)		Time data (Hr.)	
Ni	CIi	DET i	CP i	CDP i	CCT i	TI i
0	–	1	0	0	0	0
1	2	0	2165	32	132	6
2	1	0	3143	75	193	9
3	2	0	3777	120	234	6
4	2	1	7668	207	445	6
5	3	0	9972	254	572	16
6	2	1	12386	286	715	6
7	2	0	15965	351	906	6
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
47	1	0	81478	2251	4874	10
48	2	0	81963	2267	4917	7
49	1	0	82516	2314	4956	10

Regarding the production inputs, it is ideally recommended to use reliable information systems as a base [25, 26], ideally with modules of online data capture, such as the PI System (management of real-time data and events), which records automatically and in real time various data, such as production. This information can be analyzed in terms of equipment or global system, and it will depend on the physical position of sensors that monitor the production output. In general, these automatic capture systems only provide information about the state of the asset (on/off) and the time of detention, so they must be complemented with management systems of maintenance notifications and work orders [8, 15], such as the ERP's: SAP-PM, MAXIMO, ELLIPSE. This integration achieves a consolidated database to feed the GAOEM tool of analysis effectively.

GAOEM has been applied by using real data from a computer belonging to a line of pumping inert material in a mining company located in Chile.

The following table 3 presents the registration form to collect input data for the application of the GAOEM

Table 4. BPI based on time - GAOEM method.

Variable	Description
Time between Intervention **[TBI i]**	Total time between intervention i and intervention i-1. TBI i = CCT i - CCT i-1
Downtime of intervention **[DT i]**	Time during the equipment does not operate. DT i = TI i x (1 - DET i)
Operating Time **[OT i]**	Time during the equipment is in operation. OT i = TBI i – TI i-1 x (1 - DET i-1)
Cumulative Operating Time **[COT i]**	Cumulated Operating time/working time when i th intervention occur. COT i = Σ OT i
Total Cycle Time **[TCT i]**	This includes operation and intervention time. TCT i = TBI i + DT i
Planned Working time **[PWT i]**	Time the organization has planned to operate. PWT i = TBI i - DT i (to Preventive Intervention) TTP i = TBI i (to Corrective or Operational Intervention)
Cumulated Planned Working time **[CPWT i]**	Cumulative sum of planned working time. CPWT i = Σ PWT i

Table 5. BPI based on production - GAOEM method.

Variable	Description
Production between intervention **[P i]**	Production processed during the time between interventions. P i = CP i - CP i-1
Defective production between intervention [$\mathbf{DP_i}$]: [$\mathbf{CDP_i}$] - [$\mathbf{CDP_{i-1}}$].	Defective production (out of quality standard) measured for each intervention
Average Speed production between intervention [$\mathbf{ASP_i}$]	Average Speed production measured during the operating time between intervention $\mathbf{ASP_i} = \frac{\mathbf{P_i}}{\mathbf{OT_i}}$
Cumulative Average Speed production between intervention [$\mathbf{ASP_i}$]	Average Speed production measured during the cumulative operating time between intervention $\mathbf{ASP_i} = \frac{\mathbf{cP_i}}{\mathbf{cOT_i}}$
Ideal nominal cumulative production **[INCP i]**	Cumulated ideal production in chronological time (No intervention of any kind) INCP i = CCT i x NCP
Cumulative planned production **[CPP i]**	Production in the planned working time; i.e., the planned production to nominal capacity, excluding the scheduled time of preventive interventions. CPP i = CPWT i x NCP
Cumulative expected production **[CEP i]**	Expected production during functioning time, i.e., the expected nominal production capacity, excluding the downtimes. CEP i = COT i x NCP

method. According to the selected pumping process, the work units will be tons [Ton.] and hours [Hr.] respectively.

In the case of variable nominal capacity of production [NCP], this is an input that depends on the operational requirement or the process design. For the case study, the requirement is 20 tons/hour.

2.3 *Basic performance indicators*

From the input data, GAOEM requires to calculate some basic performance indicators (BPIs), which are classified according to time and production in the following Tables 4, 5 and 6.

Considering the input data from table 3, the basic performance indicators are calculated (Table 6).

In the above tables, specifically for the column (Ni), the data is supplemented with a (*) or (**); the first links the event with a corrective intervention, while the second links it with a preventive intervention. The unsigned data correspond to the operational detentions.

2.4 *Partial Efficiency Indicators*

Particularly for the context of the mining industry, Table 7 briefly presents the strategic indicators (partially effective) to estimate the overall efficiency indicator (OAE). Both are made instantly at the ith intervention and in an accumulated form over time, as described in the basic performance indicators.

$OAE = A \times U_e \times P \times Q$, or $OAE = U \times P \times Q$, these are the instant or accumulated points of view.

Table 6. a: BPIs Based on time (Hr.).

N i	TBI i	DT i	OT i	COT i	TCT i	PWT i	CPWT i
1**	132	6	132	132	138	132	132
2*	61	9	55	187	64	55	187
3**	41	6	32	219	38	41	228
4**	212	0	206	424	206	206	433
5	127	16	127	551	143	127	560
6**	143	0	127	678	127	143	703
7**	192	6	192	869	198	192	894
..	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..
47*	41	10	32	4494	42	41	4690
48**	43	7	33	4527	40	43	4733
49*	39	10	32	4559	42	32	4765

The following Table 8 presents the results of the partial efficiency indicators and the overall efficiency indicator.

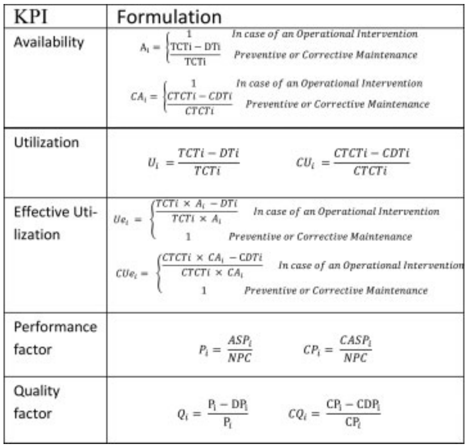
2.5 *Partial and total effectiveness indicator control panel*

GAOEM incorporates a graphical control panel comprising partial and total performance indicators of the

Table 6. b: BPIs Based on production (Tons).

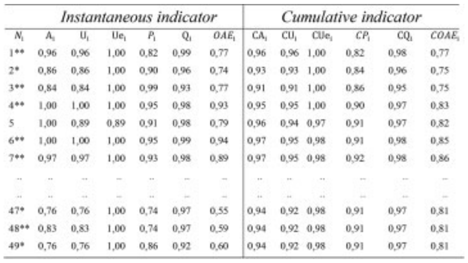
N i	DP i	ASP i	CASP i	INCP i	CPP i	CEP i	P i
1**	2165	32	16,4	16,4	2640	2640	2640
2*	978	43	17,9	16,9	3850	3730	3730
3**	634	45	19,8	17,3	4670	4550	4370
4**	3892	87	18,9	18,1	8900	8660	8480
5	2304	47	18,2	18,1	11430	11190	11010
6**	2414	32	19,0	18,3	14290	14050	13550
7**	3580	65	18,7	18,4	18120	17880	17380
..	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..
47*	476	14	14,9	18,1	97470	93790	89870
48**	485	16	14,7	18,1	98330	94650	90530
49*	553	47	17,3	18,1	99110	95290	91170

Table 7. Formulation of partial efficiency indicators.



KPI	Formulation
Availability	$A_i = \begin{cases} 1 & \textit{In case of an Operational Intervention} \\ \frac{TCTi - DTi}{TCTi} & \textit{Preventive or Corrective Maintenance} \end{cases}$ $CA_i = \begin{cases} 1 & \textit{In case of an Operational Intervention} \\ \frac{CTCTi - CDTi}{CTCTi} & \textit{Preventive or Corrective Maintenance} \end{cases}$
Utilization	$U_i = \frac{TCTi - DTi}{TCTi}$ $CU_i = \frac{CTCTi - CDTi}{CTCTi}$
Effective Utilization	$Ue_i = \begin{cases} \frac{TCTi \times A_i - DTi}{TCTi \times A_i} & \textit{In case of an Operational Intervention} \\ 1 & \textit{Preventive or Corrective Maintenance} \end{cases}$ $CUe_i = \begin{cases} \frac{CTCTi \times CA_i - CDTi}{CTCTi \times CA_i} & \textit{In case of an Operational Intervention} \\ 1 & \textit{Preventive or Corrective Maintenance} \end{cases}$
Performance factor	$P_i = \frac{ASP_i}{NPC}$ $CP_i = \frac{CASP_i}{NPC}$
Quality factor	$Q_i = \frac{P_i - DP_i}{P_i}$ $CQ_i = \frac{CP_i - CDP_i}{CP_i}$

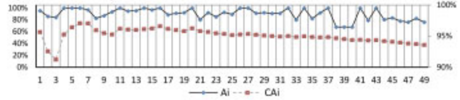
Table 8. Results of partial and total efficiency - Instantaneous and cumulative indicator.



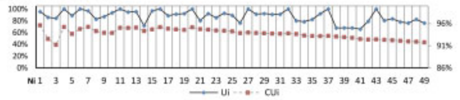
Instantaneous indicator							Cumulative indicator					
N_i	A_i	U_i	Ue_i	P_i	Q_i	OAE_i	CA_i	CU_i	CUe_i	CP_i	CQ_i	$COAE_i$
1**	0,96	0,96	1,00	0,82	0,99	0,77	0,96	0,96	1,00	0,82	0,98	0,77
2*	0,86	0,86	1,00	0,90	0,96	0,74	0,93	0,93	1,00	0,84	0,96	0,75
3**	0,84	0,84	1,00	0,99	0,93	0,77	0,91	0,91	1,00	0,86	0,95	0,75
4**	1,00	1,00	1,00	0,95	0,98	0,93	0,95	0,95	1,00	0,90	0,97	0,83
5	1,00	0,89	0,89	0,91	0,98	0,79	0,96	0,94	0,97	0,91	0,97	0,82
6**	1,00	1,00	1,00	0,95	0,99	0,94	0,97	0,95	0,98	0,91	0,98	0,85
7**	0,97	0,97	1,00	0,93	0,98	0,89	0,97	0,95	0,98	0,92	0,98	0,86
..	..	..	..	..	..	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	..	..	..	..
47*	0,76	0,76	1,00	0,74	0,97	0,55	0,94	0,92	0,98	0,91	0,97	0,81
48**	0,83	0,83	1,00	0,74	0,97	0,59	0,94	0,92	0,98	0,91	0,97	0,81
49*	0,76	0,76	1,00	0,86	0,92	0,60	0,94	0,92	0,98	0,91	0,97	0,81

asset. The continual monitoring of these indicators allows identifying the origin of the production losses individually, giving periodic information of the status of the process in order to manage the continuing improvement effectively.

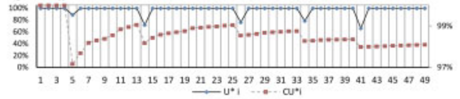
Graph 1: "Availability".



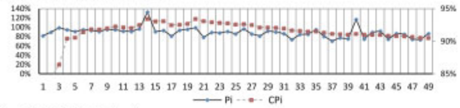
Graph 2: "*Utilization*".



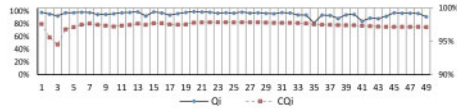
Graph 3: "*Effective Utilization*".



Graph 4: "Performance Factor".



Graph 5: "Quality Factor".



Graph 6: "Overall Asset Effectiveness".

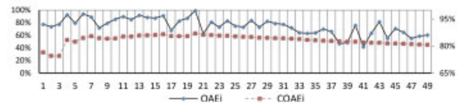


Figure 2. Graphical control panel for effectiveness performance indicators.

The control panel consists of six charts. These are constructed from a main chart that will consist of the performance indicator of interest, partial or total (axis y) depending on the cumulated number of intervention (Ni) for the ith intervention (axis x). The information in each chart must be read and interpreted with the following considerations:

- The instant result of the indicator (between events of intervention) is represented with a dark blue diamond of equivalent size for each outcome indicator, joined by a continuous line of the same color. The main x-axis (left side) is the hub to which the results should be read.
- The cumulated result of the indicator (trend) is represented by a dark red square of equivalent size for each outcome of the indicator, connected by a dotted line of the same color. The x-axis side (right side) is the hub to which the results should be read.

Below, the six graphs are presented in Figure 2.

The GAOEM control panel should be complemented with two new graphical proposals of analysis, which together make up more than one indicator, whether with a partial efficacy character, or key performance indicators.

Each proposal integrates 3 sub-graphs aligned in their result according to the axis x (number of intervention). Each graph is unique in its construction, analysis, results interpretation and conclusions. Below, Figures 3 and 4 are presented. After each graph

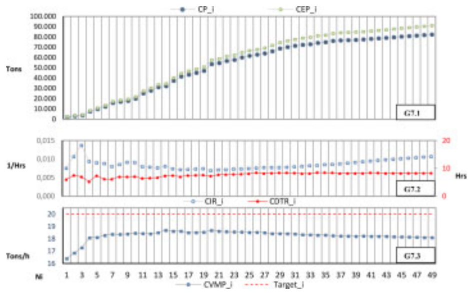


Figure 3. Graphical control panel for production gaps analysis and its primary causes.

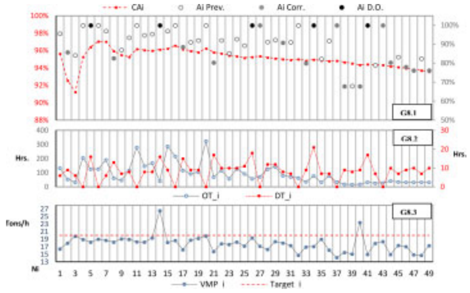


Figure 4. Graphical control panel for analysis of trends in production and its primary causes.

are detailed some reading rules and the potential events to identify.

The control panel has a filter that allows visualizing by period of interest and by class of intervention. This functionality will depend exclusively on the analyst user.

Reading rules:

- G7.1 represents the cumulated behavior of the real and the expected production (tons).
- G7.2 represents, using both axis, the behavior of the frequency of cumulated intervention (main axis Y reading – left) and the cumulated average repair rate (secondary axis Y reading – right). The units are 1/Hrs. and Hrs. respectively.
- G7.3 represents the cumulated average speed of production and, through a red dotted line, the nominal rate of design of the equipment under analysis (20 Ton/hour).

Potential events to identify:

- Trend in the production rate through concave or convex curve behavior.
- Trend in frequency of intervention, highly related to reliability; and trend in repair rate, related to maintenance.
- Primary hypothesis about the causes of the trend (acuteness or chronicity of interventions and sub/over use of the asset).

Reading rules:

- G8.1 represents, in the first place, the accumulated behavior of the availability indicator (%) by a red dotted line (reading with main axis Y – left). In addition, the instant availability is plotted at the end of each intervention I (reading with secondary axis Y – right) while stressing the classification of the operation on each result of availability (circumference) the classification of the intervention according to the color indicated: dark grey (operational intervention), light grey (corrective maintenance) and white (preventive maintenance).
- G8.2 represents, by using both axis, the instant operational time behavior (reading with main axis Y – left) and the instant downtime service behavior (reading with secondary axis Y – right, red color). The units are hours respectively for both axis.
- G8.3 represents the instant production speed and, through a red dotted line, nominal rate of the design of the equipment under study (20 Ton/hour). The units are tons respectively.

Potential events to identify:

- Trends in availability behavior.
- Representation of the kind of intervention in the maintenance strategy.
- Randomness and trends in operating times and times of intervention and detention of equipment.
- Under load or overload of the equipment, seen from the point of view of the production speed variability and the difference with the speed established as nominal working.
- Primary hypothesis about presence of patterns of aging in assets.
- Primary hypothesis about the effect of the maintenance action on the performance of the asset.
- Primary hypothesis about the effect of under or over workload in reliability and maintainability respectively.
- Primary hypothesis about the effect of reliability and maintainability in the outcome of availability. Chronic and acute phenomena.

3 CONCLUSIONS

This article develops a methodological framework proposal for the design, control and monitoring of key performance indicators for operations and maintenance, discriminating the main factors that influence on the effectiveness of the process. GAOEM proposal is complemented with a graphic panel of monitoring of partial and total effectiveness of indicators, two integral graphs of multiple information, analysis and interpretation. This graphic tool facilitates the search for efficiency losses in the operation. Having an overview of performance is a key factor as support for the control of the operation, from a point of view which places maintenance management as one of the main pillars for reducing production losses and, therefore, maximizing business benefits.

The control panel (eight graphs) can maintain a continuous control of all the indicators and identify the origin of production losses individually, providing periodic information on the status of the process and managing the continuous improvement effectively.

GAOEM provides answers to all the questions initially raised in table 1, showing its effectiveness to support the maintenance and production areas.

GAOEM can be used as a tool of interest for diagnostic, control and monitoring of indicators, as well as a tool for the search of phenomena of the life cycle of assets or those that result from improper operation and/or maintenance, identifying their root causes a priori.

To achieve the GAOEM goals efficiently and effectively, it is advisable to elaborate a high performance information system at an early stage of the implementation that allows predefined consultations and analysis. From a practical standpoint, it is important to design the relationship between all possible sources of information, their processing and the result of a consolidated information system that meets the requirements of GAOEM. Obviously this process must be supervised and supported by the experience and knowledge of the organization and the responsible staff. Also, it is possible that the requirements are not 100% resolved by the current information system of the organization, which would force the creation of a supplementary system and/or the modification of the current system. In that case the collaborative work of people with extensive knowledge of the current available information systems will be critical.

The authors recommend the integration with other tools that focus their analysis on complementary indicators, such as the GAMM [29] focused on an analysis for the maintenance management and GAOM [30] focused on the operation and production.

Regarding the applicability, in addition to the mining industry, the board can be adapted to other production processes with similar interests in control and analysis, as the case of the petrochemical industry, cellulose, brewer, among others.

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General framework about graphical analysis for operation management

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ABSTRACT: This paper introduces a general framework about a graphical method that facilitates decision-making concerning the operation in an industrial plant. The proposed tool "Graphical Analysis for Operation Management Method" (GAOM) allows us to visualize and analyze parameters related to production, integrating aspects of asset maintenance and/or systems. GAOM integrates production and maintenance based on the TPM model, that is to say, integrated management believes that prioritizes the use of quantitative management techniques that allow the strategy to bring the day to day operation, thus facilitating optimal decision-making. On the one hand, allows control existing production deviations in relation to the objectives set by the organization, and on the other, considers related aspects such as availability, repair time, and cumulative production. The GAOM method is inspired by the GAMM (Graphical Analysis for Maintenance Management) method, published by the authors (LB, AC and PV) in 2012 (Barbera et al. 2013).

1 INTRODUCTION

The need to improve productivity has required further integration of maintenance management to production management, with the ultimate goal of producing at minimum cost. To achieve these goals, practical and easily implemented tools are needed, allowing the identification of potential improvements in the production process. According to J. Fleischer (2006) the competitiveness of manufacturing firms mainly depends on variables such as the availability and productivity of their production equipment, and typically maintenance management has been analyzed independently to the management of production.

Understanding this context, design tools and methods are necessary to facilitate the analysis and identification of losses in the production process, answering common questions in the area of production and maintenance (Table 1). On the other hand, the lack of quality information, mainly due to poor collection and complex data analysis processes (Kaplan & Norton 1992, March & Hevner 2007), requests simple procedures for data collection and management facilitating the interpretation, analysis and new knowledge (March & Hevner 2007, Park 2006, Pomponio & Le Goc 2014, Watson et al. 2002).

Here are some questions generally required by the area of production and maintenance, presented in Table 1.

The main analyzed references to propose and conceptualize the GAOM method, mainly related to management control tools, are: Maintenance Management (Crespo 2007), Balanced Scorecard (BSC) (Biasotto et al. 2012, Kaplan & Norton 1992, Muchiri & Pintelon 2008), Total Productive Maintenance (TPM) (Ireland & Dale 2001, Ahuja & Khamba 2008), Overall Equipment Effectiveness (OEE) (Muchiri & Pintelon 2008) and the GAMM (Graphical Analysis for Maintenance Management) Method (Barbera et al. 2013).

Table 1. Some important questions to be answered by the tool.

Operations/ production area	Maintenance area
1. Which is the operating/running time between interventions "preventive intervention" and "corrective Intervention"?	Which is the frequency of "corrective interventions" between "preventive interventions"?
2. What is the non-operating time for "operational intervention"?	How variables are the "repair times" for preventive interventions and corrective intervention?
3. Which is the real rate of production for equipment and overall system?	How variables are the "functioning times" after a preventive interventions and a corrective intervention?
4. Which is the difference between "real production" and "planned production"?	Which is the effect of maintenance management decisions over performance indicators as: intervention time and operation/ running time?

2 GAOM METHOD

2.1 *Introduction*

The GAOM method is constructed from a database that integrates information from the production process through three classes of information: intervention (number of intervention, type of intervention, required/not required stoppage), production (cumulative production, cumulative defective products, and cumulative production target) and time (cumulative calendar time, duration of interventions).

GAOM integrates this information through calculation of indicators related to timing information, production and quality, evaluating production yields and maintenance. To facilitate analysis, GAOM presents information graphically, using scatter diagrams, integrating performance indicators on the same graph.

2.2 *Input information*

The input information is necessary for the success of GAOM method. The classification is presented in Tables 2 (2.a; 2.b; 2.c).

It must be emphasized that the measurement of throughput is taken at the output stage of the production process. Also, it works under the assumption that the actual production process does not exceed the settled nominal production capacity of it. First, is recommended to analyze a system from the overall point of view, identifying production deviations and the most important

Table 2.a. Intervention information.

Class	Description
N° intervention **[Ni]**	Assigns the number of occurrence of the intervention ith. It is a natural number under consecutive order
Stop/do not stop **[DET i]**	Reports whether the intervention stopped **(0)** or not stopped **(1)** the operation. It is a Binary variable.
Type of intervention **[CI i]**	Corrective intervention **(CM)**, associated with the value 1. It is a maintenance action after the occurrence of a failure. **[CI i = 1]** Preventive intervention **(PM)**, associated with the value 2. It is a maintenance action prior to a failure. **[CI i = 2]** Operational intervention **(OI)**, associated with the value 3. Do not execute a maintenance action. It generates a detention or reducing capacity performance. **[CI i = 3]**

Table 2.b. Time information.

Class	Description
Cumulative Calendar Time **[CCT i]**	It is the cumulative time when the ith intervention occurs. Counted from the beginning of the evaluation horizon (T = 0)
Time of Intervention **[TI i]**	Time duration requested for the ith intervention. Related to the Time to repair.

Table 2.c. Production information.

Class	Description
Cumulative Production **[CP i]**	It is the cumulative production when the ith intervention occurs. Counted from the beginning of the evaluation horizon (T = 0)
Cumulative Defective Production **[CDP i]**	It is the cumulative defective production (out of quality standard) when the ith intervention occurs. Counted from the beginning of the evaluation horizon (T = 0)
Nominal Production Capacity **[NCP]**	Nominal capacity of the process. It must be settled by operation.

loss factors. Then, the equipment analysis will be interesting to determine the main causes of deviation or to refine the analysis.

As was introduced, Figure 1 represents two possible analysis scenarios (equipment and process, respectively), showing at the same time (red points), where the measurement of the production input data could be captured.

2.3 *Scatter diagram and basic performance indicators*

To represent information in a clear and simple manner, GAOM uses a scatter diagram of Cumulative Production (CP_i) based on the cumulative number of interventions (N_i) for the i-th intervention occurred along the time horizon.

The data presented in Table 3 correspond to equipment used in mining process, specifically for a pumping line which transports inert material. Considering this, it is possible to generate the scatter diagram of the cumulative production (Fig. 2). This diagram allows the analyst to evaluate the distribution and trend of cumulative production.

According to the information related to "input information" (Table 2), it is recommended to collect the data considering the format shown in Table 4.

From input information, GAOM requires to calculate some Basic Performance Indicators (BPI), which are classified based on time or production (Tables 5 and 6).

2.4 *Integrated databases and graphs construction*

For subsequent analysis GAOM requires to develop two new integrated databases, linking the above data and basic indicators. Next are presented in Tables 7 and 8.

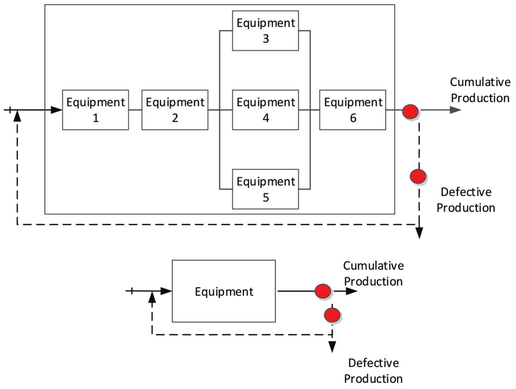

Figure 1. Analysis for process or equipment point of view.

Table 3. Historical data of interventions and cumulative production (Tons).

Accumulated production for each intervention (Tons)					
N(i)	CP i	N(i)	CP i	N(i)	CP i
1	2165	18	45236	35	74992
2	3143	19	47243	36	76264
3	3777	20	53699	37	76751
4	7668	21	54792	38	77045
5	9972	22	56873	39	77301
6	12386	23	57894	40	77646
7	15965	24	60228	41	78241
8	17095	25	61817	42	78715
9	17992	26	62939	43	79238
10	20192	27	64174	44	79850
11	25311	28	66217	45	80457
12	27989	29	68847	46	81002
13	31248	30	70279	47	81478
14	32024	31	71517	48	81963
15	37540	32	72452	49	82516
16	41590	33	73062		
17	43490	34	74375		

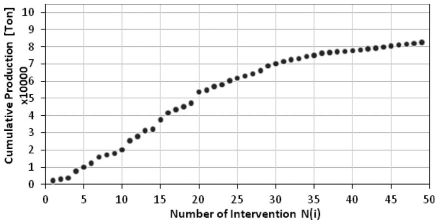

Figure 2. Scatter diagram of cumulative production.

Table 4. Standard format for data collection.

Data collection format						
Intervention data			Production data (ton)		Time data (hour)	
N i	CI i	DET i	CP i	CDP i	CCT i	TI i
0	–	1	0	0	0	0
1	2	0	2165	32	132	6
2	1	0	3143	75	193	9
3	2	0	3777	120	234	6
4	2	1	7668	207	445	6
5	3	0	9972	254	572	16
6	2	1	12386	286	715	6
7	2	0	15965	351	906	6
8	1	0	17095	405	974	13
9	2	0	17992	448	1034	7
10	2	0	20192	530	1157	8
11	2	1	25311	640	1445	8
12	2	0	27989	684	1592	8
13	2	0	31248	709	1768	8

Table 5. BPI based on time—GAOM method.

Basic indicators based on time	
Variable	**Description**
Time between Intervention **[TBI i]**	Total time between intervention i and intervention i – 1. TBI i = CCT i – CCT i – 1
Downtime of intervention **[DT i]**	Time during the equipment does not operate. DT i = TI i × (1 – DET i)
Operating Time **[OT i]**	Time during the equipment is in operation. OT i = TBI i – TI i – 1 × (1 – DET i – 1)
Cumulative Operating Time **[COT i]**	Cumulated Operating time/working time when i th intervention occur. COT i = Σ OT i
Total Cycle Time **[TCT i]**	This includes operation and intervention time. TCT i = TBI i + DT i
Planned Working Time **[PWT i]**	Time the organization has planned to operate. PWT i = TBI i – DT i (to preventive intervention) TTP i = TBI i (to Corrective or operational intervention)
Cumulated Planned Working Time **[CPWT i]**	Cumulative sum of planned working time. CPWT i = Σ PWT i

Table 6. BPI based on production—GAOM method.

Basic indicators based on production	
Variable	**Description**
Production between intervention **[P i]**	Production processed during the time between interventions. P i = CP i – CP i – 1
Nominal Cumulative Production **[NCP i]**	Cumulated production in chronological time (No intervention of any kind) NCP i = CCT i × NCP
Cumulative Planned Production **[CPP i]**	Production in the planned working time; i.e., the planned production to nominal capacity, excluding the scheduled time of preventive interventions. CPP i = CPWT i × NCP
Cumulative Expected Production **[CEP i]**	Expected production during functioning time, i.e., the expected nominal production capacity, excluding the downtimes. CEP i = COT i × NCP

Table 7. Cumulative production data—GAOM.

N(i)	CP i	TI i	DET i	OT i
0	0	0	1	0
1	2165	6	0	132
2	3143	9	0	55
3	3777	6	0	32
4	7668	6	1	206
5	9972	16	0	127
6	12386	6	1	127
7	15965	6	0	192
8	17095	13	0	62
9	17992	7	0	47
10	20192	8	0	116
11	25311	8	1	280
12	27989	8	0	147
13	31248	8	0	169
14	32024	16	0	41
15	37540	9	0	288
16	41590	9	1	217
17	43490	15	0	117
18	45236	9	0	93
19	47243	9	0	105
20	53699	10	1	325
21	54792	17	0	70
22	56873	10	0	117
23	57894	10	0	58
24	60228	10	0	128
25	61817	11	0	93
26	62939	18	0	58
27	64174	9	1	72
28	66217	12	0	126
29	68847	12	0	143
30	70279	8	0	80
31	71517	7	0	72
32	72452	7	1	64
33	73062	9	0	36
34	74375	21	0	77
35	74992	7	0	33
36	76264	7	0	79
37	76751	9	1	35
38	77045	9	0	19
39	77301	8	0	17
40	77646	9	0	19
41	78241	17	0	33
42	78715	7	0	27
43	79238	9	1	29
44	79850	10	0	41
45	80457	7	0	35
46	81002	9	0	32
47	81478	10	0	32
48	81963	7	0	33
49	82516	10	0	32

In Table 7, specifically for the first column (Ni), the data is supplemented with a sign (*) or (**), the first one related to corrective interventions and the second one to preventive interventions. The data without a sign will correspond to an operational intervention.

The GAOM method is constructed from a main chart of cumulative production v/s number of intervention, this being a scatter diagram of bubbles (cumulative production), where it is possible to represent individual analysis for each type of

Table 8. Nominal, planned and expected cumulative production—GAOM.

N(i)	NCP i	CPP i	CEP i
1**	–	–	–
2*	2640	2640	2640
3**	3850	3730	3730
4**	4670	4550	4370
5	8900	8660	8480
6**	11430	11190	11010
7**	14290	14050	13550
8*	18120	17880	17380
9**	19480	19120	18620
10**	20680	20320	19560
11**	23140	22640	21880
12**	28890	28230	27470
13**	31830	31170	30410
14	35360	34540	33780
15**	36330	35350	34590
16**	42400	41420	40340
17*	46920	45760	44680
18**	49260	48100	47020
19**	51420	50260	48880
20**	53690	52350	50970
21*	60370	58850	57470
22**	61760	60240	58860
23**	64440	62920	61200
24**	65800	64080	62360
25**	68560	66640	64920
26	70610	68490	66770
27*	71990	69650	67930
28**	73790	71450	69370
29**	76300	73960	71880
30*	79400	76820	74740
31**	81230	78410	76330
32**	82820	80000	77760
33*	84230	81270	79030
34	84950	81990	79750
35**	86670	83710	81290
36**	87740	84780	81940
37*	89460	86360	83520
38*	90290	87050	84210
39**	90670	87430	84590
40*	91190	87950	84930
41	91730	88330	85310
42**	92570	89170	85970
43*	93440	90040	86500
44*	94150	90610	87070
45**	94970	91430	87890
46*	95870	92330	88590
47*	96650	92970	89230
48**	97470	93790	89870
49*	98330	94650	90530

intervention, and filtering variables of interest as repair time or time between failures.

The bubble's dispersion function represents the Cumulative Production (CP i) based on the accumulated number of intervention (Ni) for the i-th intervention. The size (diameter) of the bubbles represents, relatively, the indicator result as shown in Figures 3 and 4.

The bubble's color represents the type of intervention: dark gray (corrective intervention), light gray (preventive intervention) and white (operational intervention).

Next, will be presented some important graphical analysis with GAOM.

- Graph 1: *"Analysis of time between failures"*. It displays the cumulative production in each intervention. The time between failures for each intervention (Ni) is represented by the bubble size. This graph allows to analyze the effect of interventions on production. Furthermore, by comparing the size of the bubbles it is possible to identify aging (systematic bubble size decrease) and the type of intervention phenomena, auditing the compliance of the established maintenance policy. Graph 1 is presented in Figure 3.
- Graph 2: "Analysis of intervention time." Displays the cumulative production in each intervention. The repair time for each intervention (Ni) is represented by the bubble size. This new graphic complement the analysis in graph 1, discriminating whether effect of loss production is cause of high frequency of failure (Chronic failure phenomena) or long times repair.

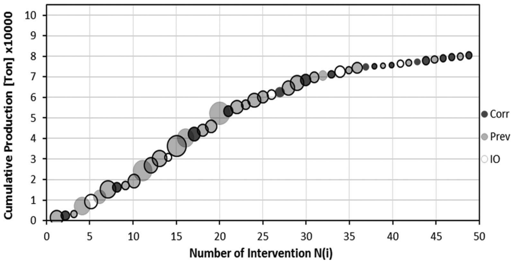

Figure 3. Graph 1. Analysis of time between failures—GAOM method.

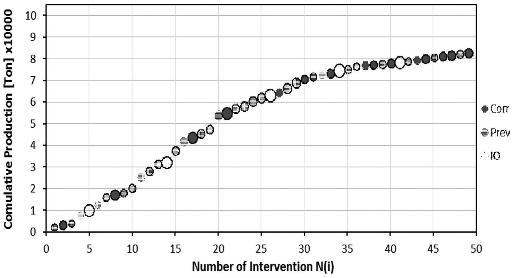

Figure 4. Graph 2. Analysis of intervention time—GAOM method.

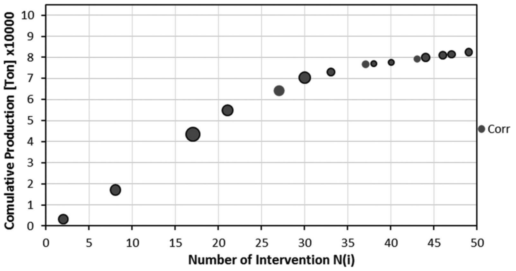

Figure 5. Graph 3. Analysis of time between failures filtering corrective interventions—GAOM method.

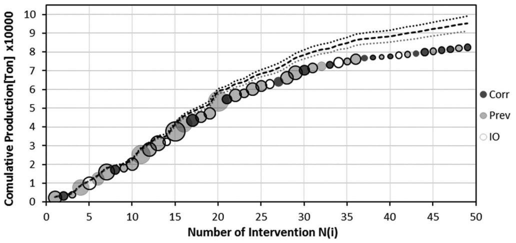

Figure 6. Graph 4. Analysis of time between failures with production targets—GAOM method.

Furthermore, by comparing the size of the bubbles can be detected labor behaviors related to: lack of discipline and/or work procedures for the development of interventions (high variability in the size of the bubbles), important differences between the repair times linked to corrective preventive interventions, atypical repair (size of bubble too big or too small), among others.

To perform an individual analysis of each type of intervention, GAOM is able to filter information based on these variables. Thus, it is possible to analyze independently the behavior of each type of intervention, allowing the user to track variables patterns, analyzing and concluding about it.

- Graph 3: "Analysis of time between failures filtering corrective interventions". This graph is equivalent to the structure presented in Graph 1, except that only allows analysis of corrective maintenance intervention. This representation allows to focus the analysis on the phenomena of failure by detecting patterns such as: main representation in the package of interventions (scatter graph), often as cumulative production (differences in vertical axis), imperfect repair resulting in premature failures (size small bubbles), aging, among others.
- Graph 4: "Analysis of time between failures and production targets". This chart shows the set of possible variables in a single graph. The dotted lines represent the expected ideal, planned and real production. Integrally, this chart allows us to analyze the impact of different phenomena intervention on production, compared to an ideal and/or planned scenario.

According to Graph 4, losses of efficiency generate deviations between real and ideal or planned production. It is necessary to control these deviations identifying the expected production target and the existing deviations. GAOM facilitates the analysis of these deviations, relating to.

Ideal production corresponds to the expected production accumulated over time (ideal scenario without any kind of intervention). It is directly related to the settled nominal process capability. Displays how the process should produce under Overall Asset Effectiveness (OAE) with value 100% (Muchiri & Pintelon 2008).

Planned production corresponds to the expected production (at nominal capacity) during the work planned time. This time horizon just does not include planned intervention as a possible time for production.

3 CONCLUSIONS

This paper introduces the general framework for GAOM method, describing and exemplifying the integration of operation and maintenance variables, mainly: cumulative production, intervention times for corrective, preventive and operational interventions, operational times, and others. With GAOM it is possible to identify individual or systemic phenomenon, measuring, evaluating or auditing the impact of decision related to operational procedures or maintenance policies or strategies; as well as incorporating the tool as a "*big picture*" of process performance, supporting to control operation and maintenance management. GAOM summarizes and complements the decision process to reduce production losses and thus maximizing business benefits.

The GAOM method consists of seven input variables and one optional production variable (production target). The variables are classified in "intervention", "production" and "time". With this input data, then are calculated the work variables for the method.

GAOM supports analysts measurement, computing and validating indicators. However, it should be noted the importance of quality and quantity of historical data. It is recommended the integration with other tools that center their analysis on complementary indicators, such as the GAMM (Barbera et al. 2013) tool, focused maintenance management analysis.

The integration and next analysis of GAMM and GAOM method would integrate valuable information about operations management, production and maintenance. This would improve the optimization of integral policies for the maintenance and operation area.

Understanding the conference page number restriction, this article corresponds just to a summary of the main research related to the GAOM method, explaining the main characteristics and construction framework.

The full article responds to each question introduced, and also considers another 5 graphics to support operational and maintenance analysis and decision process.

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Probabilistic performance assessment for crushing system.
A case study for a mining process.

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Abstract: The productive performance of a system is mainly determined by its design specifications such as volume, capacity and processing speed; however, it is also conditioned on the reliability of its equipment, the logic be-hind the operation of the process and the availability of its overall system. In this viewpoint, these features are relevant to estimate the throughput, and need to be given due account in proper dimensioning and management.

Significant modelling complexities can arise when accounting for realistic conditions for multi-production, storage flexibility, recirculation, setups, and random times of operations and repairs. Within an integrated, systemic view of the production process and related productivity performance, these issues must be treated by fusing the methods of reliability and availability analyses with those of production process engineering.

This article propose an integrated probabilistic modelling to analyze, evaluate and compare the performance of a Crushing line under specific operational criteria, considering the characteristics of its equipment and the systemic setting in which they are embedded. The resilience characteristic is an important real factor of this kind of process, so will be analyzed in detail.

According to, the software RelPro® will be used to model the Crushing System (mining process in Chile). This software was developed in Java language, based on Monte Carlo simulation (simulation by event). This modelling creates the flexibility needed to model the complex behaviour of high-dimensional systems.

Keywords: System Modelling, Performance Simulation, Simulation by event, Resilience restriction, Primary Crushing Process.

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1. INTRODUCTION

In current literature, there are several investigations whose objective is to identify the principal factors that directly affect the maximization of throughput and economic benefit, those that converge at empirical consideration of reliability, maintainability, and availability indicators (RAM). The traditional reliability analyses based on a logical and probabilistic modelling contributes to improve key performance indicators (KPIs) of a system [1], a direct influence in determining optimal operation designs [2]. In this line, there are many alter-natives available for reliability analysis of systems employing analytical techniques, like Markov Models [3], Poisson [4], and other techniques [5]. The systematic study are usually based on techniques like Reliability Block Diagrams (RBDs) [6, 7], Fault Trees (FTs) [8], Reliability Graphics (RGs) [9], Petri Nets (PNs) [10], among others; which allow for the logical relationships that underlie the behaviour or dynamics of the process. In some applications, specifically when complex and dynamic systems are involved, these techniques must be adapted or extended with further considerations. An excellent example for this is the adaptation of de classic RBD to measure the effects of the buffer inventory level on the performances of the production line [11].

In practice, the performance of a production line is limited by intrinsic characteristic of each one of the equipment that contributes to the overall functioning, the most important are:

- ✓ Nominal Capacity of the machinery/stations/production equipments.
- ✓ Reliability and Maintainability behaviour

- ✓ Maintenance Planning
- ✓ Operational Restrictions
- ✓ Setting or structure of the system

Their corresponding limitations can create bottlenecks in the production which must be accurately evaluated and effectively corrected [12, 13]. Then, the operational reliability and productivity of a system must be analyzed in a combined fashion to allow optimal exploitation of resources to achieve the set production goals [3]. This requires that a number of characteristics of the production processes be given due account, such as the last mentioned.

In this line, the primary concern of this proposal is to build a model to analyze and project the system performance (mining process) involving realistic criteria last mentioned. This proposal directly derives from industrial requirements in the context of design evaluation.

Monte Carlo simulation is used as the modelling framework to capture the realistic aspects of equipment and system behaviour [15, 16]. This approach creates the flexibility needed to model the complex behaviour of high-dimensional systems.

The most important motivation for using Monte Carlo simulation comes from the possibility of building a realistic (probabilistic) model of a system’s (stochastic) behaviour, which allows the creation of realistic system production life representations by sampling the occurrence of discrete random events from their characteristic probability distribution functions. This method is commonly used to solve complex problems by random sampling [17, 18]. It involves the generation of random or pseudo-random numbers that enter into an inverse probability distribution, resulting in as many scenarios as the number of simulations made [19]. The results of this process being far more informative than what can be inferred from a few designed scenarios, e.g. generated for ‘what if’ type analyses.

In this paper a Monte Carlo simulation-based analysis procedure is used to analyze a real-world case study from mining engineering. The simulation model will be implemented in the RelPro environment [20], estimating the expected behaviour of performance of each piece of equipment and of the system as a whole, and generates related confidence bounds that account for the statistical variability in behaviour.

RelPro is an analysis and simulation tool that can be used to model continuous and discrete production systems, such as conveyors, transfer lines, mass production lines, fleets, and others. RelPro allows the reproduction of randomized replications of a system model using highly complex logic and it provide innovative and efficient algorithms to analyze and evaluate different scenarios, supporting making decision process related to design and operational conditions, aiding of course the business result.

The motivation of this work is to build an integral probabilistic modelling for a mining process (Crushing line), which constitutes a systematic procedure to model, simulate and sensitize the selected production process, all under innovative algorithms and friendly RelPro environment.

According to the aims, this article is organized as follows: in section ‘‘System Description,’’ the application is presented in detail; in sections ‘‘Modelling of the system’’ the process is modeled under RelPro environment and briefly summarized according to the general methodology; in section ‘‘Data Analysis,’’ will be explained the importance of the data and reliability and maintainability analysis with RelPro.

Finally, case study is solved in section “Simulation Model” and some concluding remarks are given in section ‘‘Conclusion’’. .

2. SYSTEM DESCRIPTION

In the context of mining industry, this paper presents and analyses a real case study developed in a cooper Open pit mine, specifically for the primary crushing (PC) (Fig. 1), which normally is the first stage in a comminution process [1]. Crushing is normally carried out on ‘run-of mine’ ore, and the objective is to reduce the size of the material from the mine, which is then transported by some conveyor belts to a stockpile.

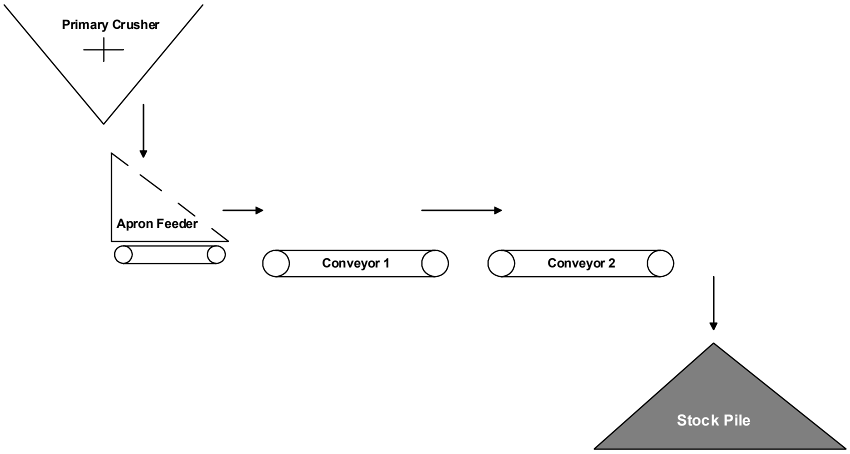


Fig. 1 Process diagram for the primary crushing process

As a brief description of the process involved, after a mining company has removed overburden, extraction of the mineral ore begins using specialized heavy equipment and machinery, such as loaders, haulers, and dump trucks, which transport the ore to processing facilities using haul roads. After, the ore is dumped into the primary crusher; then an apron feeder is connected controlling the gravity flow of bulk solids, providing an uniform feedrate to the next receiving belt conveyor. Two next belt conveyors are connected to the apron feeder, to finally feed the stockpile.
The main characteristics of the primary crushing process shown in Fig. 1 are listed in Table 2.

Table 1. Primary crushing process information

Equipment	ID	Basic Fucntion
Primary Crusher	CH_001	Mineral size reduction
Apron Feeder	FEED_001	Control of the gravity flow of bulk solids, providing an uniform feedrate to the next receiving belt conveyor
Conveyor Belt 1	CONV_001	Transport the crushed mineral to the next conveyor
Conveyor Belt 2	CONV_002	Transport the crushed mineral to the stock pile

3. MODELLING OF THE SYSTEM

The logic behind the operation (functional dependency) of the process can be understood by using a simple question What' if? It means that it is necessary to recognize the effect of some random or planned state change of any production equipment/machinery of the process over the system, that involve the effect in terms of functioning and work load capacity over the others machineries, subsystems and overall system. Normally, there are two possible states, degradation (normal established functioning) and not degradation (failure state, preventive intervention or operational detention) [21].
The four components of the process are connected in a simple serial setting, which implies that any single failure will cause the entire system to fail. A major operational criteria that benefits the outcome (second scenario to model and sensitive) is the resilience of the process when the primary crusher or the apron feeder fails. When one fails, or both simultaneously, the downstream process will continue to work for the next 40 minutes. This operational feature is equivalent to if both machineries have the ability to accumulate material during normal operation, been capable to supply 30 to 40 minutes of downstream operation
The resilience scenario leads to a cold standby system [22], which satisfies the usual conditions (i.i.d. random variables, perfect repair, instantaneous and perfect switch, queueing). It is important to consider tree important features:

- ✓ To model it, it is necessary to create a "virtual" stand by equipment, with specific parameters of failure and repair.
- ✓ As preliminary criteria, the failure distribution must be a Uniform Distribution with parameter of life equal to range of the resilience time estimated (30 – 40 minutes).
- ✓ As preliminary criteria, the repair time distribution of the "virtual" equipment must be equivalent to the repair time distribution of the main equipment. It is a conservative scenario.

The Fault tree diagrams are developed (Fig. 2 and 3) to support the understanding and representation of the both process scenarios.

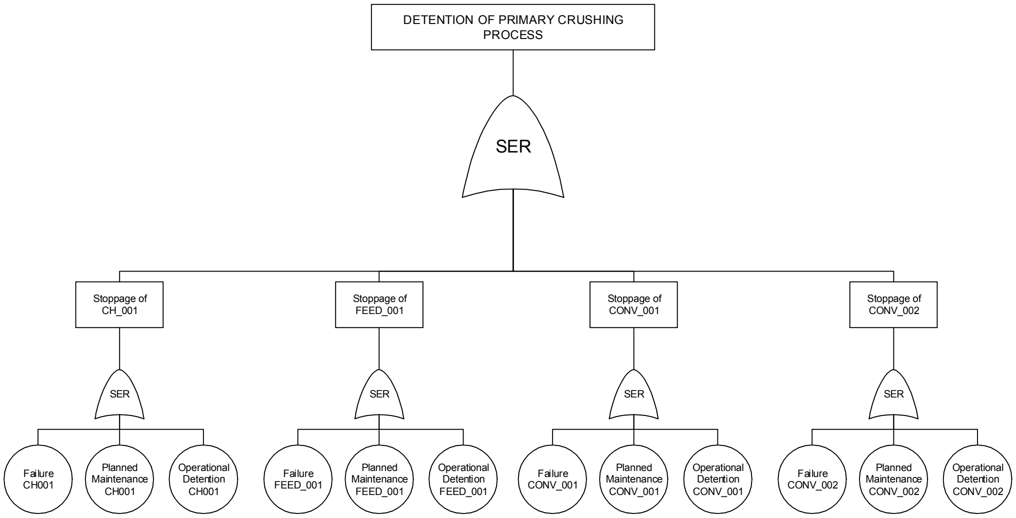


Fig. 2 FT representation of the primary crushing process - immediate effect

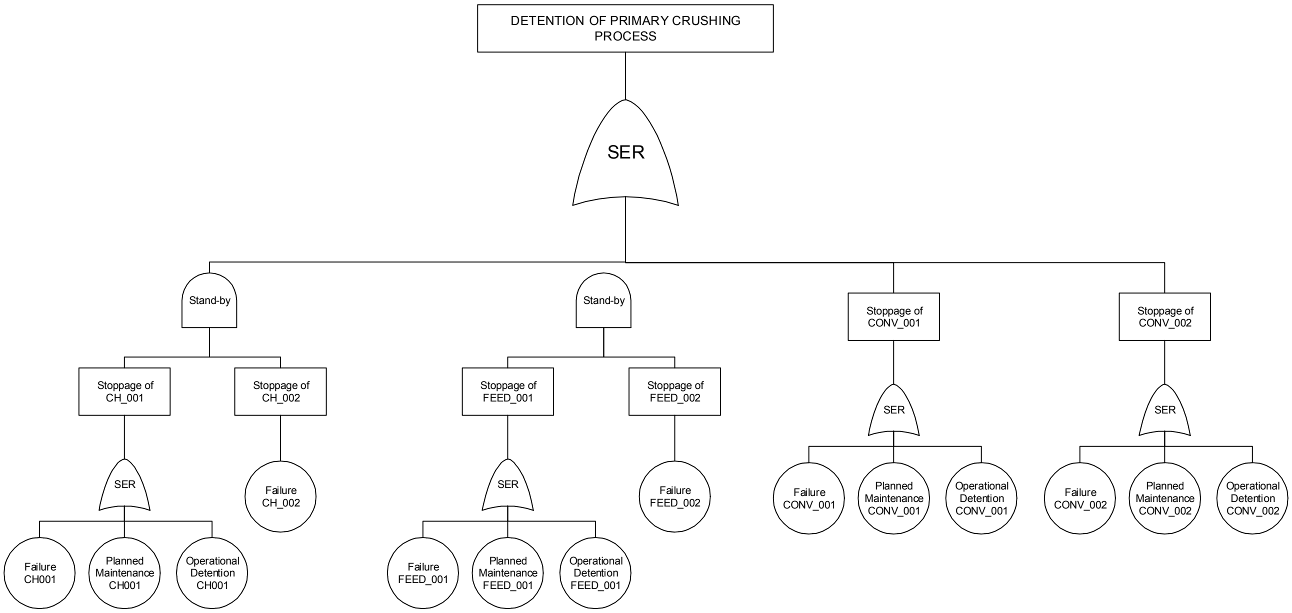


Fig. 3 FT representation of the primary crushing process – resilience approximation

So, process modelling in software RelPro must consider the traditional scenario (immediate effect of detention) and the constraint scenario (resilience approximation). With this, the analysis results will be enriched.

As was indicated at the beginning of the paper, the motivation of this work is to build an integral probabilistic modelling, so the next section will explain and analyze the statistical data related to: Times To Failure (TTF) associated to reliability and Time To Repair (TTR) related to maintainability.

The simulation will not include parameters linked to operational stoppages nor planned maintenance. This consideration just simplified the analysis in terms quantity of analysis, but not in terms of quality or methodology, since these considerations can be modelled and integrated just like a serial setting as was graphically represented by the FT diagrams (Fig. 2 and 3).

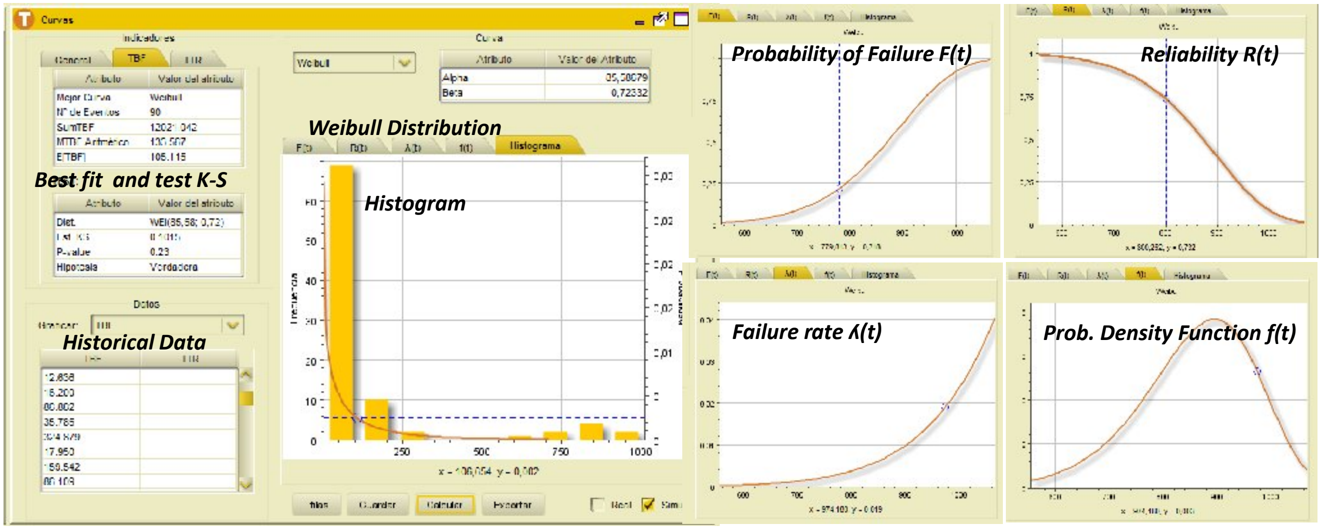
4. DATA PARAMETERIZATION

The definition of the probability distributions is commonly used to describe the failure and repair processes of the equipment. Different types of statistical distributions are examined and their parameters are estimated by using, as mentioned before, the RelPro Application. The software fits several distribution models based on the historical data, and it is possible to choose and use a preferred model, or accept the distribution recommended by the software (Weibull 2 parameters, Exponential, Lognormal, Normal, Dirac Delta and Uniform).

The following step in data management is to determine the nature of the equipment involved in the process, so the distributions must be selected under relevant stochastic models, according to the behaviour of the data in terms of trend and independence.

Analyzing the historical data of the equipment involved, independence and trend indicators are calculated. In the first instance, this feature is observed graphically. For this, some graphics of cumulative time to failure (TTF) observe the behaviour of trends and then dispersion charts of successive lives to observe the degree of correlation of variables or independence. Also, the Laplace test was applied. Due to space limitations, these are not included.

The Software RelPro allowed to estimate all the parameters for each probability density function (TTF and TTR), and no trend was identified. As an example, Fig. 4 shows the parameterization for the primary crusher, specifically for times to failures (TTF).



Atributo	Valor del atributo
Mejor Curva	Weibull
Nº de Eventos	90
SumTBF	12021,042
MTBF Aritmético	130,567
E[TBF]	105,115

Atributo	Valor del Atributo
Alpha	85,58079
Beta	0,72332

Atributo	Valor del atributo
Dist.	WEI(85,58; 0,72)
Est. K-S	[illegible]
P-value	0.23
Hipótesis	Verdadera

TBF	TTR
12,838	
16,200	
80,802	
35,765	
324,879	
17,950	
150,542	
80,109	

Fig. 4 Probability density function for primary crusher

Fig. 4 summarize the information about: histogram of failure, Accumulated probability of failure F(t), reliability R(t), failure rate ʎ(t), probability density function of failures f(t) and the relevant information about the Kolmogorov–Smirnov tests [23] (statistical goodness-of-fit test selected in RelPro).

Table 2 summarizes main parameters and key indicator related to reliability and maintainability.

Table 2. Reliability and maintainability information

Equipment	Time To failure Parameterization				Time To Repair Parameterization			
	Best fit Distribution	Parameter 1	Parameter 2	MTBFi	Best fit Distribution	Parameter 1	Parameter 2	MTTRi
CH_001	Weibull	α=85,72	β=0,72	106	Normal	μ=4,1	σ=1,12	4,10
FEED_001	Weibull	α=82,01	β=0,87	88	Normal	μ=3,9	σ=1,31	3,90
CONV_001	Exponential	λ=0,054		19	Normal	μ=1,2	σ=0,60	1,20
CONV_002	Weibull	α=15,84	β=0,65	22	Exponential	λ=0,76		1,32

5. SIMULATION MODEL

To model and simulate the process, it is necessary to consider all the specific operating conditions and all realistic restrictions that exist and are physically respected by the real process. The main characteristics of each piece of equipment to be considered in the simulation model are listed in Table 2, and the restriction related to the logical and functional dependency were explained in detail in the section: Modelling of the system. The FT for both main scenarios helps to build the model in RelPro environment.

The simulation must consider an overall production rate, which is similar for all equipment according to the serial setting explained. Each piece of equipment must be able to produce at the rate required by the process, this being totally or partially as demanded by the system.

For this specific case, the rate considered is 3000 ton per hour, and it assumes that the ore input is equivalent to the ore rate output demanded by the process. This means that in any case the system will stop for lack of supply or for capacity problem after the second conveyor belt (feeding the stockpile).

The graphical models (base for the simulation) developed in RelPro are presented and discussed next.

5.1. About RelPro

Processing systems depends in part on the operating logic established, for this RelPro has efficient algorithms dedicated exclusively to the representation and analysis of these logics. Most of continuous simulators, or discrete but with continuous control and monitoring variables, perform the calculation of indicators and identification of states through monitoring at certain intervals of time (usually very small), this procedure is slightly efficient when it is compared to vision oriented just to the state change of components of the system. That means that the monitoring and consultation is performed only when something in the system changes state, either random or planned condition. For this, a continuing evaluation of the state of each system element is required. So, in the field of simulation, RelPro is a simulator based on discrete-event occurrence, in contrast with continuous simulation in which the simulation continuously tracks the system dynamics over time. The impact generated depends exclusively on the established functional dependencies and diagrammed in RelPro environment.

The main elements of the modeling are: Tree of components representing the hierarchical structure in the systems, and the flow chart includes:

- ✓ Actionable nodes representing systems, subsystems or equipment, logic-nodes configuration (method by which distributed or flow conditions over the subsequent process) input and output nodes (clarifies the input and output of material processed).
- ✓ Bows, correspond graphically to arrows, represent the transfer of flux.

The graphical models (base for the simulation) developed in RelPro are presented and discussed next

5.2. Simulation Modelling and Analysis in RelPro environment

Now, as was mentioned at the end of the section “Modelling of the System” RelPro will consider the traditional scenario (immediate effect of detention) and the constraint scenario (resilience approximation). With this, the simulation modelling is:

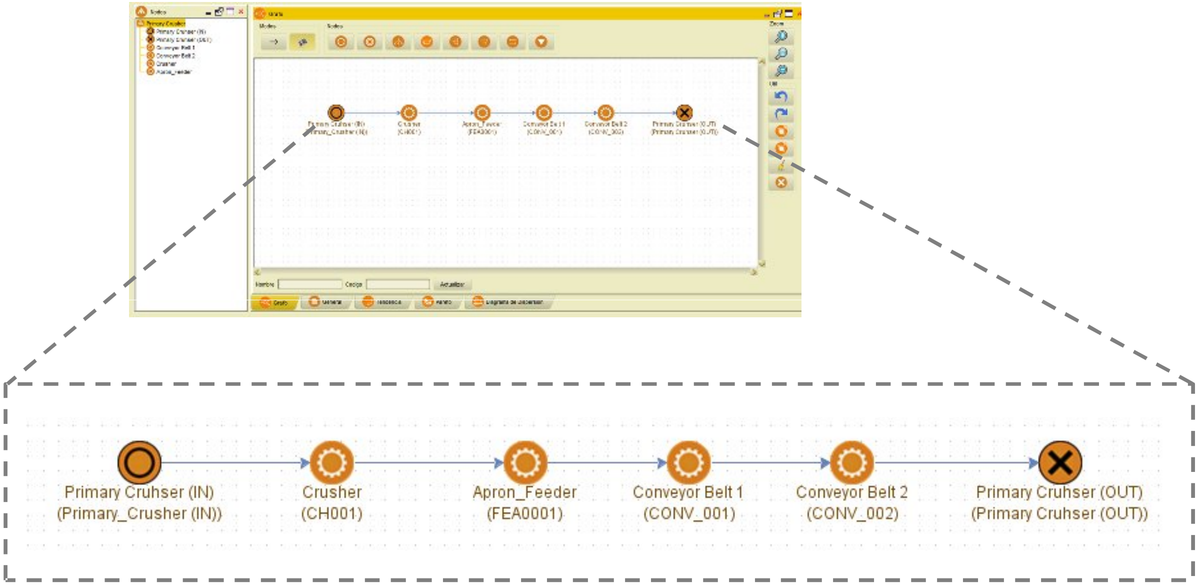


Fig. 5 Graphical representation of modelling in RelPro environment – Immediate effect scenario

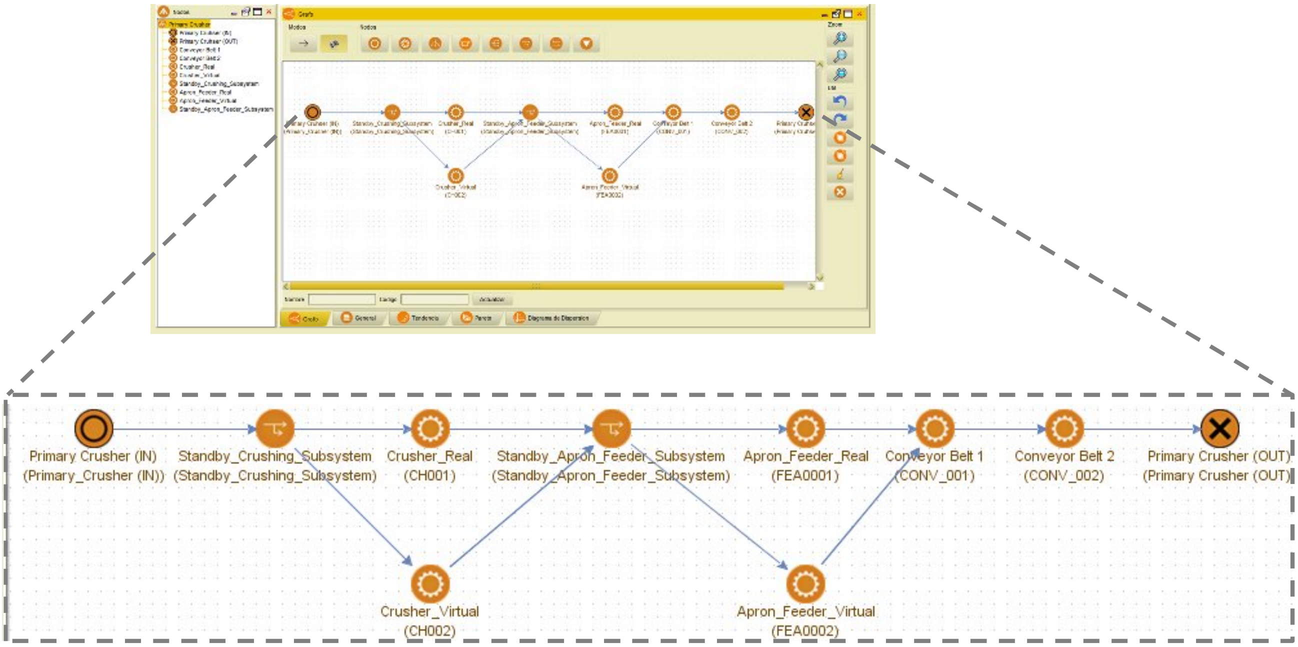


Fig. 6 Graphical representation of modelling in RelPro environment – Resilience approximation scenario

For both scenarios is required (inputs) the data about the characteristics of each piece of equipment considered in the simulation (See table 2). Furthermore, for "resilience approximation" it is assumed that the standby equipments (virtual machineries for modelling) come into operation immediately after the failure of the primary machinery (Crusher and Apron Feeder) and the repair actions are independent. This consideration is traditionally recognized as cold-standby [22].

As we know, the resiliencie time for primary machineries is between 30 and 40 minutes, so the parameters of life degradation and repair time will be modelled by Uniform Distribution..

5.2. Simulation Results

A total of 1000 replication were performed over a time horizon of 1 year (8760 hours) of operation. The main reason for selecting this simulation horizon, executed 1000 times, is to provide a representative sample to generate histograms readable and compelling indicators. In addition, some pieces of equipments have small times to failure values (e.g. Belt Conveyors); so on the time horizon will become very significant. The results of the 1000 simulation are summarized in table 3 and table 4. The performance indicators to measure are: Mean % Availability, Mean % of Operation, MTTF, MTTR and the Mean of total production of the sys-tem.

The results for the immediate effect scenario are:

Table 3. Summary of simulation results – Immediate effect scenario

Equipment	Indicator of Performance				
	Mean % Availability	Mean % Oper. Time	Mean Production (MM Tons)	MTTF	MTTR
CRUSHING SYSTEM	81,25%	81,25%	21,355	8,24	1,90
CH_001	96,10%	81,25%	21,355	90,41	4,11
FEED_001	95,72%	81,25%	21,355	75,06	3,93
CONV_001	93,75%	81,25%	21,355	16,10	1,23
CONV_002	94,18%	81,25%	21,355	18,56	1,32

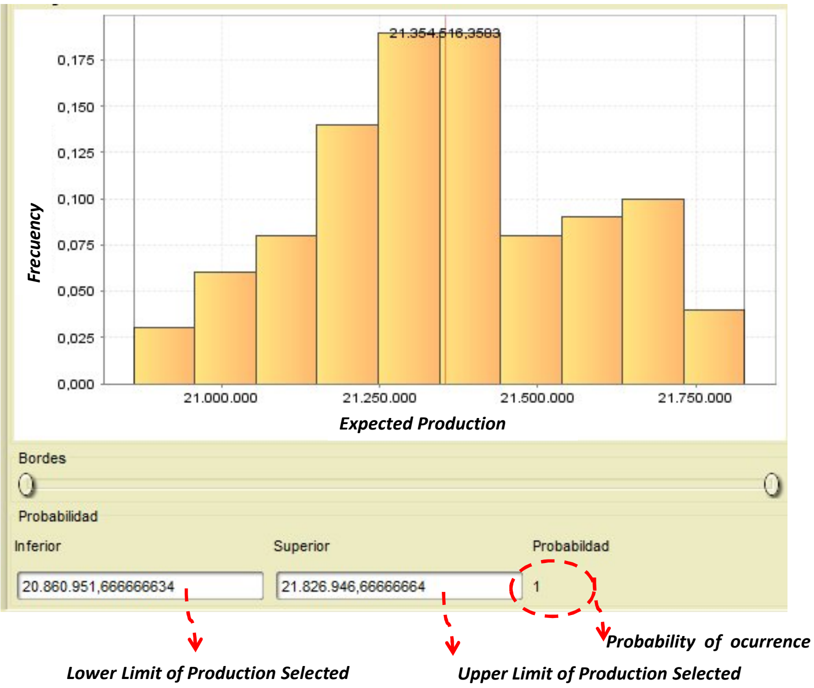
According to the results and in relative terms, CONV_001 and CONV_002 will be the critical equipment in terms of availability (93,75% and 94,18%). The expected mean production of the system is 21,355 Million of Tons, equivalent to 7.118,17 hours of operation. As the model simulation does not include planned stoppages (maintenance or operational stoppages), the % mean availability of the crushing system is equal to the % mean operational (81,25%).

Another important result, from the systemic point of view, is the frequency of failure which is each 8,24 hours of functioning, and the mean time to repair is around 1,9 hours. These last indicators are the main reason of the low % mean operational time, mainly represented by the high frequency of failure of the system. As the logical configuration is in series, any change state (planned or not planned) of any equipment will impact over the change state of the overall system.

So, to improve the reliability of the overall process (decrease the frequency of system failure) will be necessary to improve the reliability of conveyors CONV_001 and CONV_002, this means increasing the mean times to failure, 16,10 and 18,56 respectively.

A direct analysis of maintainability indicators suggest that we should not be concern about it, however, if the direct cause of the reliability results of single equipments is the low quality of maintenance execution (e.g. poor technical skills of maintenance personnel, spare parts in poor condition, lack of work procedures, environmental conditions, and other.), efforts should be focused to correct deviations in reliability and maintainability.

Next will be presented the histogram of Production (Tons). The histograms for availability and % of Operational time can be obtained directly from the Software RelPro.



Inferior: 20.860.951,666666634

Superior: 21.826.946,66666664

Probabildad: 1

Probability of ocurrence

Lower Limit of Production Selected

Upper Limit of Production Selected

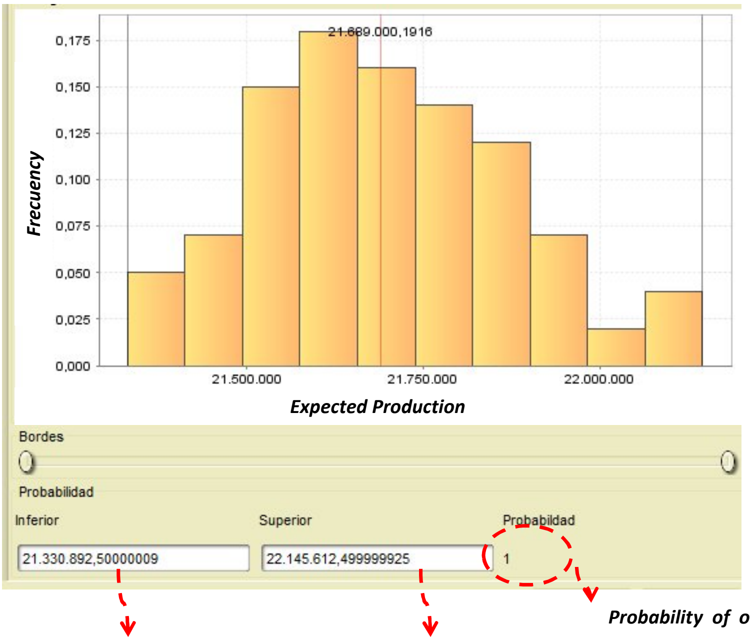
Fig. 7 KPI´s Histograms for Immediate effect scenario

Table 4. Summary of simulation results – Resilience approximation scenario

Equipment	Indicator of Performance				
	Mean % Availability	Mean % Oper. Time	Mean Production (MM Tons)	MTIF	MTTR
CRUSHING SYSTEM	82,53%	82,53%	21,689	8,42	1,78
STANDBY PRIMARY CRUSHER SUBSYSTEM	96,89%	82,53%	21,689	93,44	3,53
CH_001	96,29%	82,53%	21,568	92,85	4,12
CH_002	14,56%	82,53%	0,012	0,59	4,11
STANBY APRON FEEDER SUBSYSTEM	96,43%	82,53%	21,689	76,63	3,29
FEED_001	95,79%	82,53%	21,547	76,04	3,88
FEED_002	15,19%	82,53%	0,142	0,59	3,91
CONV_001	93,76%	82,53%	21,689	16,36	1,23
CONV_002	94,25%	82,53%	21,689	18,87	1,30

Again, conveyors are the critical equipment in terms of availability. The primary crusher and Apron feeder subsystems have increased their availability thanks to the virtual equipments configured into the RelPro environment. The mean production is 21,689 Million of Tons, equivalent to 7.229,66 hours of operation. Similarity to the previous scenario simulated, the model simulation does not include planned stoppages (maintenance or operational stoppages), so the % mean availability of the crushing system is equal to the % mean operational time (82,53%). The latter is a key indicator to compare the results between simulation models. The results of frequency of failure (8,42 hours of functioning) and mean time to repair (1,78 hours) also have improved, supporting the increased production (+ 0.3 million of tones) and availability (+1,3%) results.

Next will be presented the histogram of Production (Tons). The histograms for availability and % of Operational time can be obtained directly from the RelPro environment.



Probabilidad

Inferior: 21.330.892,50000009

Superior: 22.145.612,499999925

Probabildad: 1

Probability of ocurrence

Lower Limit of Production Selected

Upper Limit of Production Selected

Fig. 8 KPI´s Histograms for Resilience approximation scenario

The variability in the production level shown in Fig. 7 and 8 is due to the stochastic characteristic of the behaviour of the equipments in the system. Also, the convergence and concentration of area around the aver-age of the production histogram supports the good results obtained with 1000 simulations.
As a special case, the % mean availability for virtual equipment (CH_002 and FEED_002) is calculated considering that the time horizon for the calculation is only during the primary equipment repair, so this percentage represent the mean % of time where the virtual equipment support to the primary equipment, and its equivalent to 14,5% and 15, 19% respectively.

Comparing the results of the simulated scenarios, it can be concluded:

- ✓ The considered resilience contributes significantly to the outcome of the business, validated by the increased availability, operation time and the expected production.
- ✓ The Standby approximation modeled in RelPro meets the objectives pursued by analysts.
- ✓ For both, the main problem is the reliability of the selected critical equipment, this because of the high frequency of failure. So, next research must be focused to identify the primary causes of high frequencies trough, e.g. root cause analysis [24].
- ✓ Maintainability is controlled and requires no further attention since the focus of improvement is the reliability.

6. CONCLUSION

Performance analysis must be an integral part of mine engineering assessment and operational management, controlling operating plants or evaluating new designs project. Simulation is powerful tool to estimate performance (design stage), even more when characteristics of reliability, maintainability, productivity and functional dependencies features are integrated to the model. The main result of this paper is a new modelling approach to simulate a production plant, developing a case study of a real mining process (primary crushing process), including a specific scenario with a restriction formally known as resilience. It was implemented via the simulation program RelPro.
The numerical results clarify the effect of the resilience in the performance results (1,3% increase in availability and production) and allows preliminarily identify critical equipment or possible

bottlenecks, in terms of reliability and maintainability. The detail of results are clearly specified and explained in last section.
As a summary, the result of the modelling allows:

- ✓ Project the performance of each piece of equipment, subsystems, and overall crushing systems.
- ✓ It is possible to identify the equipment (s) with the worst performance – Potential bottlenecks.
- ✓ Identify responsibilities in the outcome of system performance, acknowledging directly the effect of reliability and maintainability.
- ✓ With the histograms of the simulation will possible to make a decision with a level of risk (probability), e.g. Fig. 7 and 8 shows the histogram of production and the respective probability.
- ✓ Compare the result for both scenarios, calculating the expected effect of the operational restriction (resilience). Furthermore, for future research, the time of resilience may be sensitized and evaluated if necessary.

Future possibilities to analyze with RelPro:

- ✓ Histograms for each selected indicator of performance.
- ✓ Add new indicator, such as: number of failure events, preventive events and operational detention events; total time of corrective maintenance/preventive maintenance/operational detentions; budget for maintenance, and others.
- ✓ Basic cause of the Operational stoppages, it refers to intrinsic detention of the equipment (e.g. misalignment of the conveyor belts) or Operational stoppages propagated from other piece of equipment in the system (e.g. if the belt conveyor 1 fail the rest of the system will stop obligatory. So, this event will be recorded as a detention propagated in the rest of equipments of the system).
- ✓ The modelling method may be adopted in order to analyze more complex systems or process.

Future possibilities to sensitize and analyze with RelPro:

- ✓ Probabilistic parameters of life and repair (genetic).
- ✓ Preventive frequencies at equipment level.
- ✓ Design of the process, involving redundancies, priorities, load sharing and overload capacity. Furthermore, recirculation characteristics.
- ✓ Time of resilience (increase or decrease) and evaluate the impact evolution.

Finally, the authors encourage the use of this model to evaluate the expected performance as early as at the design stage, ensuring highly efficient investments and positive impacts on future productivity.

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COLABORACIÓN EN LIBROS - CÁPITULOS

[1] Carlos Parra, Adolfo Crespo, Vicente González-Prida, Fredy Kristjanpoller, **Pablo Viveros** & Gabriel Llort. "Case study on a maintenance and reliability management model proposal: A third set of locks project in the Panama Canal". Chapter 1. Optimum Decision Making in Asset Management. An imprint of IGI Global. USA, 2017. ISBN: 9781522506522 (ebook).

[2] José Contreras, Carlos Parra, Adolfo Crespo, Vicente González-Prida, Fredy Kristjanpoller & **Pablo Viveros**. "Model of a performance measurement system for maintenance management". Chapter 9. Optimum Decision Making in Asset Management. An imprint of IGI Global. USA, 2017. ISBN: 9781522506522 (ebook).

[3] **Pablo Viveros**, Fredy Kristjanpoller, Adolfo Crespo, René Tapia & Vicente González-Prida. "Mathematical and Stochastic Models for Reliability in Repairable Industrial Physical Assets". Chapter 12. Practices through Energy Engineering and Asset Management. Engineering Science Reference (an imprint of IGI Global). USA, 2015.

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[5] Vicente González-Prida, Luis Barberá, **Pablo Viveros** & Adolfo Crespo. "Dynamic Analytic Hierarchy Process: AHP method adapted to a changing environment". Advanced Maintenance Engineering, Services and Technology. 2012. Elsevier Science. (Ed.) Márquez, C. ISBN: 9781622769254.

PUBLICACIONES NACIONALES ACEPTADAS - SCIELO

[6] **Pablo Viveros**, Raúl Stegmaier, Fredy Kristjanpoller, Luis Barberá, Adolfo Crespo. Proposal of a Maintenance Management Model and its Mains Tools Support. Ingeniare. Revista chilena de ingeniería, vol. 21 Nº 1, pp. 125-138, 2013.

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[1] **P. Viveros,** A. Crespo, F. Kristjanpoller, R. Stegmaier, E. Johns, T. Grubessich, L. Barberá. General framework about graphical analysis for overall effectiveness management. The Annual European Safety and Reliability Conference (ESREL). Glasgow, Scotland. Sept 25-29, 2016. ISBN: 978-1-138-02997-2.F.

[2] T. Grubessich, **P. Viveros,** R. Stegmaier, F. Kristjanpoller, V. González-Prida, F. Pérès. General framework methodology to increase organizational learning in the field of asset management. The Annual European Safety and Reliability Conference (ESREL). Glasgow, Scotland. Sept 25-29, 2016. ISBN: 978-1-138-02997-2.

[3] F. Kristjanpoller, A. Crespo, M. Lopez-Campos, **P. Viveros,** T. Grubessich. Reliability assessment methodology for multiproduct and flexible industrial process. The Annual European Safety and Reliability Conference (ESREL). Glasgow, Scotland. Sept 25-29, 2016. ISBN: 978-1-138-02997-2.

[4] **P. Viveros**, A. Crespo, L. Barberá, F. Kristjanpoller, R. Stegmaier, E. Johns, T. Grubessich. General Framework about Graphical Analysis for Operation Management. The Annual European Safety and Reliability Conference (ESREL). Zurich, Switzerland. Sept 7-10, 2015.

[5] F. Kristjanpoller, **P. Viveros**, A. Crespo, T. Grubessich, R. Stegmaier. RAM-C: A novel methodology for evaluating the impact and the criticality of assets over systems with complex logical configurations. The Annual European Safety and Reliability Conference (ESREL). Zurich, Switzerland. Sept 7-10, 2015.

[6] T. Grubessich, R. Stegmaier, E. Johns, **P. Viveros**, F. Kristjanpoller. A Methodological Proposal to meet analysis requirements with purified information through a logical work sequence and a decision tree in the field of maintenance management. The Annual European Safety and Reliability Conference (ESREL). Zurich, Switzerland. Sept 7-10, 2015.

[7] F. Kristjanpoller, A. Crespo, **P. Viveros**, R. Mena, R. Stegmaier. A novel methodology for availability assessment of complex load sharing systems. The Annual European Safety and Reliability Conference (ESREL). Wroclaw, Poland. Sept 14-18, 2014.

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[9] **P. Viveros**, A. Crespo, F. Kristjanpoller, R. Stegmaier, E. Johns , V. Gonzalez-Prida. Probabilistic Performance Assessment for Crushing System. A Case Study for a Mining Process. In: PSAM12 - Probabilistic Safety Assessment and Management. June 22 – 27, 2014. Honolulu, Hawaii, USA.

[10]R. Tapia, **P. Viveros**, A. Crespo. An Innovative Proposal for Systemic Modeling, Analysis and Simulation in a Continuous Production Process. In: PSAM12 - Probabilistic Safety Assessment and Management. June 22 – 27, 2014. Honolulu, Hawaii, USA.

[11]**Pablo Viveros G**., René Tapia P., Johanna Gómez Q., Jesús Laor R., Erick Vargas L. “Gestión integral de activos en Minera Antapaccay: Fase de diagnóstico y evaluación preliminar”. Primer Seminario Internacional de Mantenimiento de Plantas y Equipos Mineros – MAPLEMIN 2014. Lima, Perú.

[12]**P. Viveros**, C. Nikulin, A. Crespo, R. Tapia, R. Stegmaier, E. Johns, F. Kristjanpoller. A Support System for Selecting the most suitable Spare Parts Strategy. In: 8th World Congress on Engineering Asset Management & 3rd International Conference on Utility Management & Safety. 30 Oct – 1 Nov 2013, Hong Kong.

[13]**P. Viveros**, R. Tapia, E. Johns, F. Kristjanpoller, C. Nikulin. A Creative Risk Analysis Algorithm to Support the Spare Part Decision. In: The Annual European Safety and Reliability Conference (ESREL). Holland, Amsterdam. Sept 29- Oct 02, 2013.

[14]C. Nikulin, G. Cascini, **P. Viveros**, R. Stegmaier, L. Barberá. An Algorithm for Root Cause Analysis integration based on OTSM-TRIZ: Complex Problem Analysis. In: The Annual European Safety and Reliability Conference (ESREL). Holland, Amsterdam. Sept 29- Oct 02, 2013.

[15]L. Barberá; A. Crespo; **P. Viveros**; F. Kristjanpoller. “RAM Analysis of Mining Process: A Case Study of a Copper Smelting Process in the Field of Mining, Chile”. 2nd IFAC Workshop on Advanced Maintenance Engineering, Services and Technology, A-MEST ’12, through the Conference Paper Management System of the IFAC. Seville, Spain. November 21-23, 2012.

[16]L. Barberá; A. Crespo; **P. Viveros**; C. Nikulin. Methodological Proposal for Problem Resolution in Industrial Activities Based on Failure Mode Analysis. Case Applied in the Cellulose Industry, Chile" 2nd IFAC Workshop on Advanced Maintenance Engineering, Services and Technology, A-MEST ’12, through the Conference Paper Management System of the IFAC. Seville, Spain. November 21-23, 2012.

[17]L. Barberá; A. Crespo; **P. Viveros**; R. Stegmaier “A Case Study of GAMM (Graphical Analysis for Maintenance Management) Applied to Water Pumps in a Sewage Treatment Plant, Chile"2nd IFAC Workshop on Advanced Maintenance Engineering, Services and Technology, A-MEST ’12, through the Conference Paper Management System of the IFAC. Seville, Spain. November 21-23, 2012.

[18]**P. Viveros**; René Tapia; Fredy Kristjanpoller; L. Barberá, V. Gonzalez-Prida. “Functional Stockpile Analysis in Complex Productive Systems” 2nd IFAC Workshop on Advanced Maintenance Engineering, Services and Technology, A-MEST ’12, through the Conference Paper Management System of the IFAC. Seville, Spain. November 21-23, 2012

[19]V. Gonzalez-Prida; A. Crespo; L. Barberá; **P. Viveros** “Dynamic Analytic Hierarchy Process: AHP Method Adapted to a Changing Environment" 2nd IFAC Workshop on Advanced Maintenance Engineering, Services and Technology, A-MEST ’12, through the Conference Paper Management System of the IFAC. Seville, Spain. November 21-23, 2012.

[20]I. Roda; M. Macchi; L. Fumagalli; **P. Viveros**. “On the Classification of Spare Parts with a Multi-Criteria Perspective" 2nd IFAC Workshop on Advanced Maintenance Engineering, Services and Technology, A-MEST ’12, through the Conference Paper Management System of the IFAC. Seville, Spain. November 21-23, 2012.

[21]**P. Viveros**, E. Zio, C. Nikulin, R. Stegmaier, G. Bravo. Integration of root cause analysis and theory of inventive problem solving. In: Proceedings of the 11th international Probabilistic Safety Assessment and Management Conference and The Annual European Safety and Reliability Conference (ESREL). Helsinki, Finland. June 25-29, 2012.

[22]R. Mena, E. Zio, **P. Viveros**, F. Kristjanpoller, A. Arata. Simulation and Multi-Objective Optimization of an Open-Pit Mine Truck-Shovel System by the Cross-Entropy Method. In: Proceedings of the 11th international Probabilistic Safety Assessment and Management Conference and The Annual European Safety and Reliability Conference. Helsinki, Finland. June 25-29, 2012.

[23]R. Mena, E. Zio, **P. Viveros**, F. Kristjanpoller and A. Arata. Stochastic Modeling and Simulation of an Open-Pit Mine Truck-Shovel System. 4th meeting of the EURO (The Association of European Operational Research Societies) Working Group on Stochastic Modeling. Paris, France. May 30 - June 1, 2012.

[24]G. Medina-Oliva, B. Iung, **P. Viveros**, L. Barberá, T. Ruin. Root Cause Analysis to Identify Physical Causes. In: Proceedings of the 11th international Probabilistic Safety Assessment and Management Conference and The Annual European Safety and Reliability Conference. Helsinki, Finland. June 25-29, 2012.

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CONFERENCIAS & PROCEEDING NACIONALES

[1] **Pablo Viveros**, Raúl Stegmaier, Christopher Nikulin, Vicente González, Luis Barberá, Adolfo Crespo y Carlos Parra. Aplicación e integración de procedimientos para la generación de soluciones innovadoras y sustentables, mediante la metodología RCA y teoría inventiva TRIZ. VIII Encuentro Internacional de Mantenedores de Plantas Mineras, MAPLA 2011. Antofagasta.

[2] **Pablo Viveros**, Adolfo Arata, Fredy Kristjanpoller, Vicente González, Luis Barberá y Adolfo Crespo. Aplicación del cuadro de mando integral para la mejora de la gestión de garantía—alineación estratégica". VIII Encuentro Internacional de Mantenedores de Plantas Mineras, MAPLA 2011. Antofagasta.

[3] **Pablo Viveros**, Rodrigo Mena, Roberto Villalón, Adolfo Arata. Gestión del mantenimiento mediante análisis gráfico del secuenciamiento de detenciones. VII Encuentro Internacional de Mantenedores de Plantas Mineras, MAPLA 2010. Santiago.

[4] **Pablo Viveros**, Raúl Stegmaier, Adolfo Arata, Luis Barberá, Adolfo Crespo. Modelo avanzado para la gestión integral del mantenimiento en un ciclo de mejora continua. IX Encuentro de Gestión de Activos Físicos & V International Seminar on Asset Management, EGAF 2010, Universidad Católica de Chile, Santiago.

EXPERIENCIA LABORAL - ACADÉMICA

Pregrado: Universidad Técnica Federico Santa María.

- ✓ Profesor, Uso de Software para Ingeniería Industrial (2010 – 2014)
- ✓ Profesor, Gestión de Operaciones (2016)
- ✓ Profesor, Ingeniería de Plantas Industriales (2011 – 2016)
- ✓ Profesor, Administración de la Producción (2009 – 2011)

Diplomado en Gestión de Activos y Mantenimiento: Universidad Técnica Federico Santa María.

- ✓ Profesor, Planificación y Programación de Mantenimiento (2012 – 2016)
- ✓ Profesor, Estrategias de Mantenimiento (2012 - 2016)
- ✓ Profesor, Ingeniería de Plantas Industriales (2012 - 2015)
- ✓ Profesor, Ingeniería en Confiabilidad y Mantenimiento (2012 - 2015)

Magister en Gestión de Activos y Mantenimiento: Universidad Técnica Federico Santa María.

- ✓ Profesor, Planificación y Programación de Mantenimiento (2012 – 2016)
- ✓ Simulación de Procesos (2014 – 2016)

RESUMEN EXPERIENCIA LABORAL - INGENIERÍA

Abril 2016 – a la fecha	Académico Jornada Completa, Departamento de Industrias, Universidad Técnica Federico Santa Av. España 1680, Valparaíso, Chile.
Mayo 2016 – Dic 2016	Consultor especialista en gestión de activos para Empresa de Ferrocarriles del Estado (EFE), Chile.
Mayo 2009 – Abril 2016	Profesor Part Time e Ingeniero de Investigación y Proyectos del Centro de Competitividad y Gestión de Activos, Departamento de Industrias, Universidad Técnica Federico Santa Av. España 1680, Valparaíso, Chile.
Diciembre 2014 – a la fecha	Consultor Sénior en Proyecto IC para Minera Antucoya. Implementación de Ingeniería de confiabilidad en línea de área seca. Minera Antucoya.
Julio 2013 – Abril 2014	Consultor Sénior para Proyecto de implementación de IC en área de molienda para minera Antapaccay, Perú. Implementación de mejoras acorde a las normas PASS 55, ISO 14224 y aplicación del software en gestión de activos.
Agosto 2012 – Nov. 2013.	Consultor especialista en Metro de Santiago. Diagnóstico de capacidad de talleres (L2 y L5), modelación y simulación en software Arena de escenarios de operación hasta el 2017.
Septiembre - Diciembre 2012	Consultor especialista en Minera Doña Inés de Collahuasi, Iquique. Estudio de Capacidad y Confiabilidad en líneas de Molienda, considerando el impacto que tiene la variabilidad de la carga de entrada (Ton/hora) en la confiabilidad respectiva de las líneas.
Julio - Septiembre 2012	Consultor en área de Ingeniería de confiabilidad Minera Escondida – BHP, Antofagasta. Soporte a la determinación de frecuencia optima de mantenimiento y elaboración de presupuesto 2013 para equipos principales de línea de Chancado y Correas.
Marzo – Junio 2009	Ingeniero especialista en análisis de costo de abastecimiento de carbón para Termoeléctrica Guacolda, Huasco. Chile.
2008 - 2009	Ingeniero de Proyectos y Confiabilidad, Planta de tratamiento de Aguas Servidas, La Farfana. Empresa depuradora de aguas servidas (EDAS). Grupo Suez, Edas – Degremont. Santiago de Chile.
2007	Práctica profesional en Sociedad Agrícola Dos Ríos, Empresa Productora de Leche. Participación en la implementación de un sistema de gestión, enfocado a las áreas administrativas, contables y operativas. Santiago de Chile.

COLABORACIÓN Y PARTICIPACIÓN EN ESTANCIAS DE INVESTIGACIÓN

Pasantía de Investigación en la Universidad de Sevilla durante el año 2016 (Junio - Julio, 2016).

Pasantía de Investigación en la Universidad de Sevilla durante el año 2015 (Junio - Julio, 2015).

Pasantía de Investigación en la Universidad de Sevilla durante el año 2014 (Junio - Julio, 2014).

Pasantía de Investigación en la Universidad de Sevilla durante el año 2013 (Octubre, 2013).

Pasantía de Investigación en la Universidad de Sevilla durante el año 2012 (Enero-Marzo, 2012).

Participación activa en pasantías de trabajo de investigación en la Universidad Federico Santa María (Chile) de equipos investigadores de las Universidades de Sevilla, Universidad de Nancy y el Politécnico de Milán. Con todas ellas se han desarrollado trabajos de investigación y casos de estudio que aportan conocimiento y resultados al proyecto iMaPla Integrated Maintenance Planning - European Union. (2008-2013).

Proyecto: iMaPla -Integrated Maintenance Planning 2008 - 2013
Support for training and career development of researches (Marie Curie Actions)
International Research Staff Exchange Scheme (IRSES)
PIRSES-GA-2008-23 0814
Proyecto de la Unión Europea desarrollado por el Politécnico de Milán-Italia, la Universidad de Nancy-Francia y la Universidad de Sevilla-España y el Departamento de Industrias de la Universidad Santa María- Chile.
El proyecto busca desarrollar un programa de intercambio de Profesores, Investigadores y Doctorandos, para facilitar el desarrollo de investigaciones, de manera colaborativa entre los Partners del proyecto, relacionadas a la transferencia y creación de conocimiento requerido para desarrollar métodos, modelos y aplicación de herramientas TIC asociados a la Ingeniería de Confiabilidad y a la Gestión de Activos.

Investigador en Proyecto Internacional Universidad de Sevilla

Nombre: Desarrollo de procesos avanzados de operacion y mantenimiento sobre sistemas.
Descripción: Desarrollo de procesos avanzados de operación y mantenimiento sobre sistemas cibero fisicos (CPS) en el ámbito de la Industria 4.0.
Referencia: DPI2015-70842-R Universidad de Sevilla.

COLABORACIÓN EN COMITÉ DE EVALUACIÓN CIENTÍFICA

Revisor Revista ISI: Proceedings of the Institution of Mechanical Engineers Part O-Journal of Risk and Reliability. 2014 a la fecha.

Revisor Revista SCIELO: Revista de Ingeniería DYNA. 2014 – a la fecha.

Chairman in conference sessions. The Probabilistic Safety Assessment & Management conference, 2014, Hawaii USA.

TUTORÍA DE TESIS PREGRADO Y POSTGRADO

20 tesis de pregrado. Ingeniería Civil Industrial.

40 tesis de postgrado. Magíster en Gestión de Activos y Mantenimiento.

HABILIDADES COMPUTACIONALES.

Software Nivel Avanzado:	Microsoft Office, SPSS, M. Visio, RelPro, Raptor, Weibull ++. Aplicaciones: Crystall ball, What`s, Best, Best Fit, Lingo Optimization.
Software Nivel Intermedio/Básico:	Arena, Promodel, SPSS.

IDIOMAS.

Ingles.	Nivel Avanzado
Español	Lengua Nativa