Knowledge Management 4.0

Priv.-Doz. Dr.-Ing. Fazel Ansari

May 2, 2023

Overview of the Course

Lecture (VO) and Exercise (UE)

Date	Place	Topic
07.03	Bombardier Hörsaal + HS 2	• Introduction to the course • What is a CPPS?
14.03	Bombardier Hörsaal + HS 2	• CPPS & Digital Twin in Industry 4.0 • Smart Factory concept including CRISP DM
21.03	Bombardier Hörsaal + HS 2	• Introduction to Exercise • Exercise 1: Introduction to IDS
28.03	Bombardier Hörsaal + HS 2	• Exercise 2: Advanced IDS
18.04	Bombardier Hörsaal + HS 2	• Introduction to Industrial AI and Technical Language Processing
25.04	Bombardier Hörsaal + HS 2	• Knowledge Management 4.0: Theories and Foundation
02.05	Bombardier Hörsaal + HS 2	• Knowledge-Based Maintenance
09.05	Bombardier Hörsaal + HS 2	• Knowledge Representation (Ontologies/Knowledge Graph + Industry Project
16.05	Bombardier Hörsaal + HS 2	• Expert Talk • Exercise Session III: Industrial Data Science Project with CRISP methodology
23.05	Bombardier Hörsaal + HS 2	• Exercise Session IV: Applied Artificial Intelligence in Industrial Data Science & Ontology Modelling with Protégé
06.06		

Last week...

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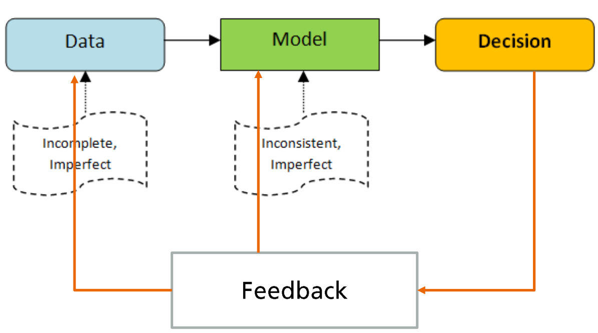
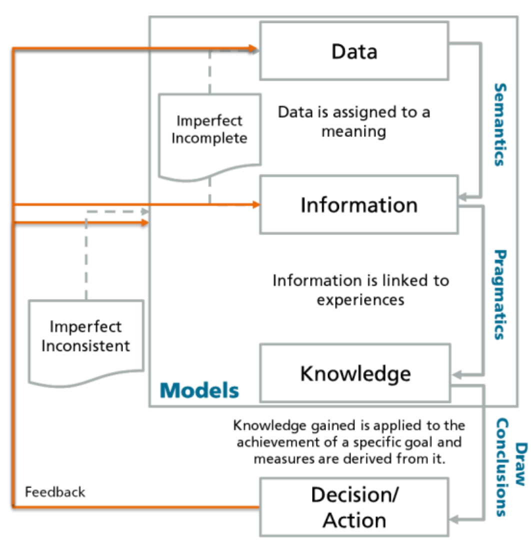
Why does KM Matter?

Because Quality of Decisions and Actions Matters!





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Definition of Knowledge Management
Summary

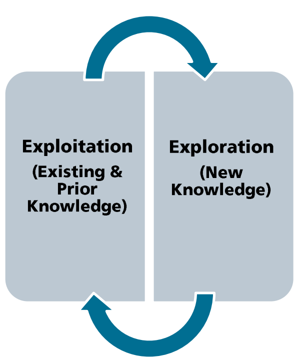
„Knowledge Management is a conscious strategy of getting the right knowledge to the right people at the right time and helping people share and put information into action in ways that strive to improve organizational performance.
- O'Dell & Grayson, 1998

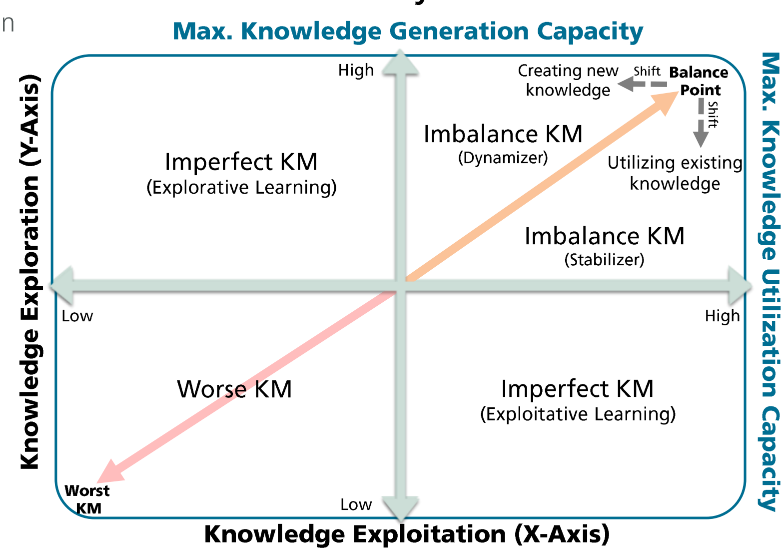
„Knowledge management (KM) is the process of creating, sharing, using and managing **collective knowledge (intelligence)** in manufacturing enterprises 4.0"
- Fazel Ansari

F. Ansari, Knowledge Management 4.0: Theoretical and Practical Considerations in Cyber Physical Production Systems,9th IFAC Conference on Manufacturing Modelling, Management and Control, Berlin, 28-30 August, 2019

Portfolio Matrix for Characterization of KM4.0 as Dynamizer and Stabilizer!
K-Exploitation and K-Exploration

KM 4.0 is the process of creating, sharing, using, managing and protecting **human-machine collective knowledge intelligence** in smart manufacturing enterprises





Ansari, F. (2019). Knowledge Management 4.0: Theoretical and Practical Considerations in Cyber Physical Production Systems, IFAC-PapersOnLine, Vol. 52, Issue: 13, pp. 1597-1602.

02.05.2023

Portfolio Matrix for Characterization of KM4.0 as Dynamizer and Stabilizer!

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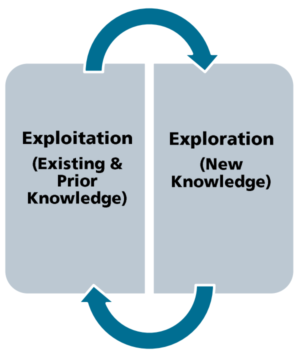

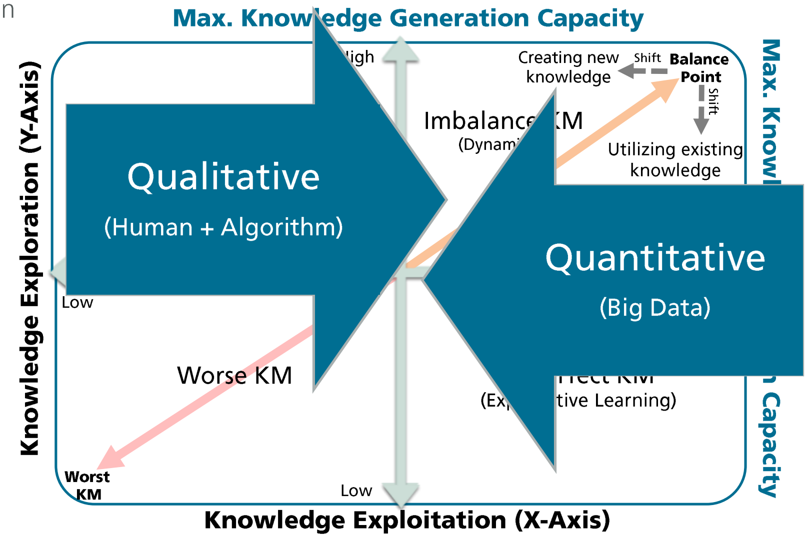

Ansari, F. (2019). Knowledge Management 4.0: Theoretical and Practical Considerations in Cyber Physical Production Systems, IFAC-PapersOnLine, Vol. 52, Issue: 13, pp. 1597-1602.

WHAT IS KNOWLEDGE-BASED MAINTENANCE?

1) Theoretical Foundations

KNOWLEDGE-BASED MAINTENANCE (KBM)

Data-driven Analysis and Modeling of RAM in Product Lifecycle Management

How OEMs and Machine Users May Gain Benefits from Data?

Reliability and durability to comply with specifications over useful life time.

Availability (Uptime) to be able to perform required functions at time *t*, *A(t)*, or over a stated period of time, *Aav*.

Products (Complex Industrial Systems) are **used** under various environmental and operational conditions in industrial value chains.

CNC-Lathe S45 @ EMCO

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Intelligent functions in products, processes, systems and services by analysis and modeling of

RAM (t)*

***RAM** (Reliability, Availability, Maintainability)

Maintainability to be timely and efficiently retained in, or restored to a required functional state, after performing maintenance actions.

Integrative modeling and analysis

Reliability	Maintainability	Availability
↔ Constant	↓ Decreases	↓ Decreases
↔ Constant	↑ Increases	↑ Increases
↑ Increases	↔ Constant	↑ Increases
↓ Decreases	↔ Constant	↓ Decreases

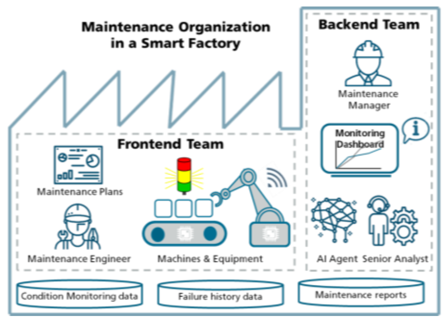
OEM: Original Equipment Manufacturer

Maintenance in Smart Factories

Frontend- and Backend Maintenance Team

- According to DIN 31051 and DIN EN 13306, maintenance is a **combination** of technical, administrative and management activities including supervision actions for keeping a **desired functional status** of an observation unit (a system/machine) during its **life cycle** i.e. retain in or restore it to the required functional state **before or after** occurrence of a **failure**.
- Maintenance activities can be classified in to two categories of "**Operation/Engineering**" and "**Management**", which leads to creation of **frontend-** and **backend teams**.
  - **Frontend team** focuses on **proper implementation** of maintenance programs, monitoring, gathering and documenting data by means of information systems.
  - **Backend team** focuses on **planning, monitoring and controlling** of maintenance activities, establishing policies, strategies, assessing the attainment of (operational and cost) objectives and accordingly (re)formulating improvement strategies as a continuous improvement process !

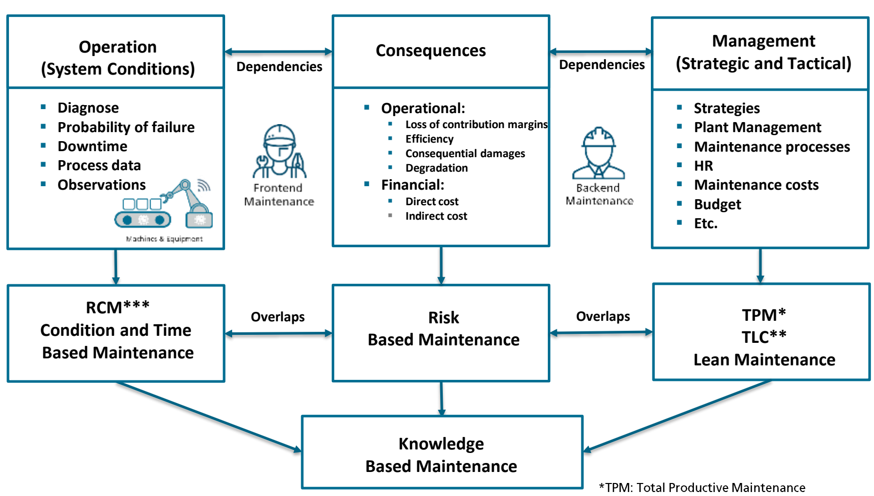
Both frontend and backend teams hold experiential knowledge, generate data and need reliable information for their actions and decisions!



Knowledge-Based Maintenance

Integrative Modeling and Analysis of RAM, based on Data and Human Experiences

- ✓ The concept of knowledge-based maintenance was coined by Pawellek 2013, however, in a holistic, generic way focusing on Organizational Learning theories.
- ✓ In (Ansari et al., 2019) this concept has been extended.
- ✓ KBM aims **at integrative analysis of RAM** considering multiple data sources, influential factors and their interrelations and thus gaining comprehensive knowledge of maintenance for improving quality of decision-making.

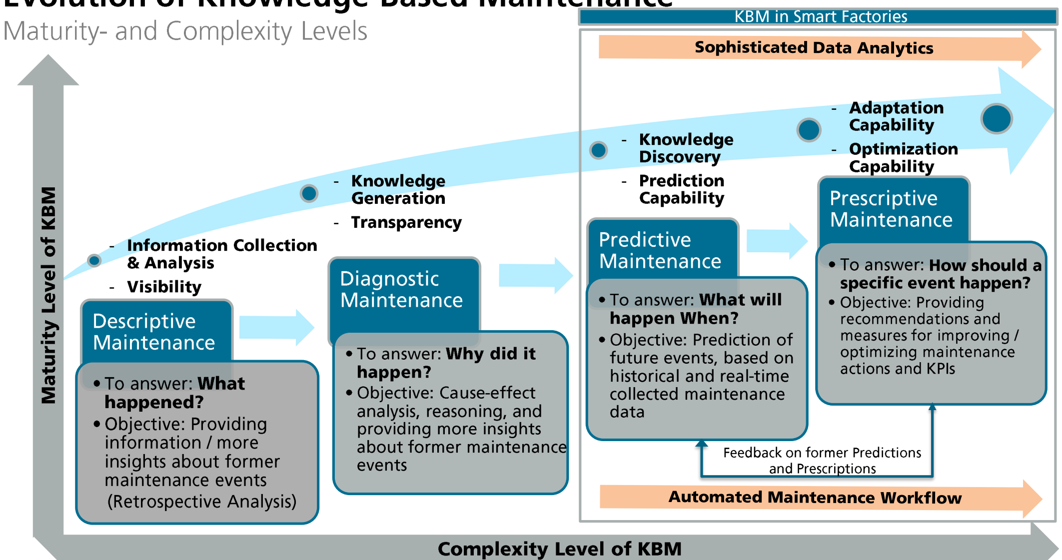


*TPM: Total Productive Maintenance
**TLC: Total Lifecycle Costing
***RCM: Reliability centered Maintenance

G. Pawellek, Integrierte Instandhaltung und Ersatzteillogistik: Vorgehensweisen, Methoden, Tools. Springer-Verlag, 2013.
F. Ansari, R. Glawar, & T. Nemeth, PriMa: a prescriptive maintenance model for cyber-physical production systems, International Journal of Computer Integrated Manufacturing, 2019.

Evolution of Knowledge-Based Maintenance

Maturity- and Complexity Levels



F. Ansari, R. Glawar, & T. Nemeth, PriMa: a prescriptive maintenance model for cyber-physical production systems, International Journal of Computer Integrated Manufacturing, 2019.

Knowledge-Based Maintenance for Modeling and Analysis of RAM

Interpretation and Challenges of KBM at the Age of Industry 4.0

- **Knowledge-Based Maintenance** is about …
  - **employing AI*** (methodologies, methods, algorithms, tools, technologies) for analyzing, modeling, predicting and reducing the **likelihood or frequency of failures** and thus **increasing availability** in production systems, gaining benefits from multi-channel, multi-structured data sources.
- **What are the challenges?**
  - Proper use of **multiple data sources**
  - Suboptimal use of **multi-structured** data
  - **Multi-modality** of data (semantic correlation of information)
  - **Multiple** and overlapping reliability-centered and maintenance **strategies** and approaches
  - **Multi-dimensionality** of maintenance organization/actors/teams, processes and IT-systems
  - **Economic** and **technical plausibility** of KBM

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*** AI:** Artificial Intelligence

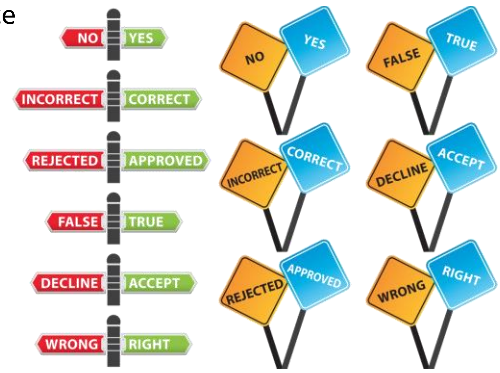
Modeling and Analysis of RAM in Maintenance of Compressors

There is no real preference and absolute answer – **It Depends on our application case!**

- What are the data sources that we may consider for modeling and analysis of RAM in maintenance of compressor units?

Answer: Multiple Data Sources

- Data from compressor manufacturers
- Data from similar products
- The existed site fault statistic data
- Failure databases
- Maintenance records
- Condition- and structural health monitoring data
- Experienced analyst's subjective judgment
- Data from Physical models?
- Data from Simulation models?

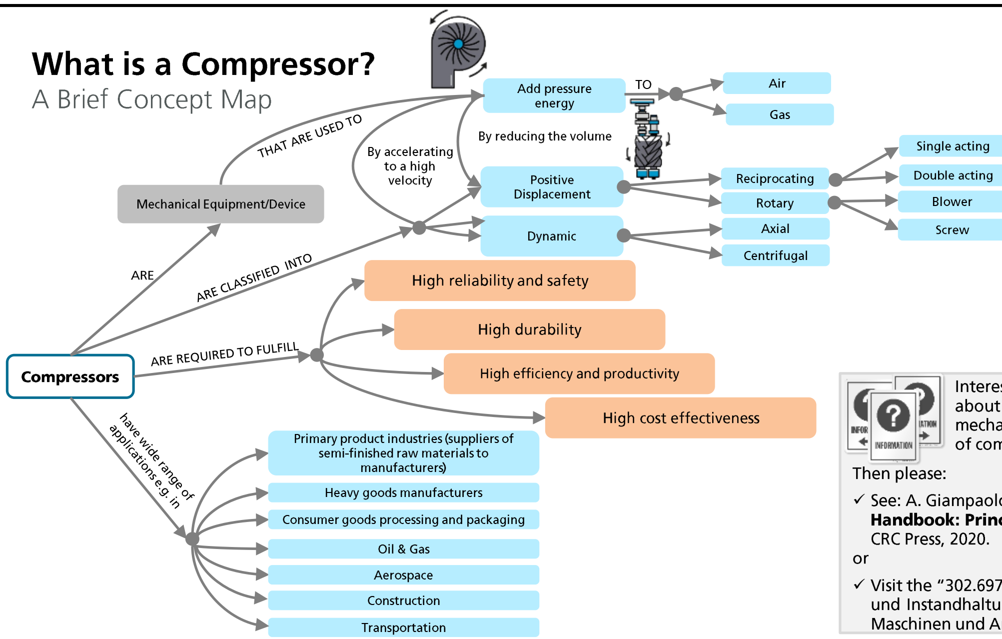


2) Knowledge-Based Approaches in Industrial Maintenance

MAINTENANCE OF COMPRESSORS IN OIL AND GAS PRODUCTION PLANTS

What is a Compressor?

A Brief Concept Map



Interested to know more about compression theory, mechanics and applications of compressors?

Then please:

- ✓ See: A. Giampaolo, **Compressor Handbook: Principles and Practice**, CRC Press, 2020.

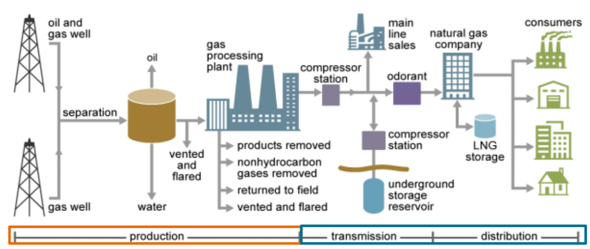
or

- ✓ Visit the "302.697 Maschinendiagnostik und Instandhaltung von Hydraulischen Maschinen und Anlagen"

Compressors

In Petroleum and Natural Gas Production Plants

- **Compressors (equipment units) are used in all aspects of petroleum and natural gas development**, e.g.
  - in the **production** segment to compress gas for fluids removal and pressure equalization with gathering equipment systems.
  - in the natural gas **processing, transmission and storage** (particularly underground storage) segments of the industry.
- **ISO 14224** specifies **typical "Types" and "Applications"** of compressors in the petroleum and natural gas industries.



Source: U.S. Energy Information Administration

Equipment Class	Type	Application
Compressor	Centrifugal Reciprocating Screw Blowers/fans Axial	Gas processing Gas export Gas injection Lift gas compression Compressed air Refrigeration

References: (Corvaro et al., 2017), (ISO 14224, 2016)

Maintainable Items of a Compressor Unit

Equipment Unit Subdivisions and related Maintainable Items

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- Maintainable items of a compressor equipment unit, independent of the compressor type, can be summarized as depicted below:

Subunit	Power Transmission	Compressor	Control & Monitoring	Lubrication System	Shaft Seal System	Miscellaneous
Maintainable Items	• Gearbox/ variable drive • Bearings • Coupling to the driver • Lubrication Seals • Coupling to the driven unit	• Casing Rotor with impellers • Balance piston • Inter-stage seals • Radial bearing • Thrust bearing • Shaft seals • Internal piping • Valves • Anti-surge system including recycle valve and controllers • Piston • Cylinder liner • Packing	• Control • Actuating device • Monitoring Valves • Internal power supply	• Oil tank with heating system • Pump with motor • Check valves • Coolers • Filters • Piping • Valves • Lube oil	• Oil tank with heating • Reservoir • Pump with motor/gear • Filters • Valves • Buffer gas • Seal oil • Dry gas seal • Seal gas • Scrubber	• Base frame • Piping, pipe support and bellows • Control-isolation and check valves • Coolers • Silencers • Purge air • Magnetic bearing control system • Flange joints • Others

References: (ISO 14224, 2016)

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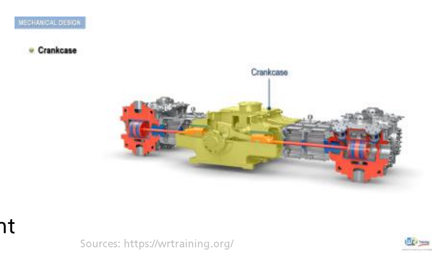
Failure Modes Effect Analysis (FMEA) of Compressor Units

Case-Study of Reciprocating Compressor

- Reciprocating compressor includes **two major functional components**:
  - **Motion mechanisms** including the crankshaft, bearing, connecting rod, crosshead, pulley or coupling, etc.
  - **Work mechanism** including cylinder, piston, valves, etc.
- Compressor is also equipped with **three auxiliary systems** including the lubrication system, cooling system and control system.
- In the main unit excluding auxiliary systems, 8 items are functionally significant Let us focus e.g. on **Crankshaft**, we may identify failure modes-cause-effects as:



Sources: https://wrtraining.org/

Failure Modes	**Failure Cause**	**Failure Effect**		
		Local Influence	**Seriously affect**	**Finally affect**
Crack	Quality fatigue	Crack propagation	Crankshaft vibration abnormal	Crankshaft fracture
Bending	High load	Crankshaft abnormal	Crankshaft vibration abnormal	Damage compressor
Fracture	Crack, High load	Shutdown	Shutdown	Severe accident

8 Significant Items

- Valves
- Crankcase
- Cylinder
- Piston
- Crosshead
- Connecting rod
- Crankshaft
- Bearing

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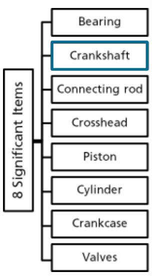
Failure Modes Effect Analysis (FMEA) of Compressor Units

8 Functionally Significant Items –FMEA, related Risks Levels and Maintenance Strategies



Part Code	Functional Items	Potential Failure Mode	Failure Cause	Failure Effect: Local influence	Failure Effect: Seriously affect	Failure Effect: Finally affect
01	Bearing	Loosening	Long-term use	Crankshaft abnormal	Crankshaft vibration abnormal	Shutdown
		Bearing bush abrasion	Long-term use, bad lubrication	Crankshaft abnormal	Crankshaft vibration abnormal	Shutdown
02	Crankshaft	Crack	Quality fatigue	Crack propagation	Crankshaft vibration abnormal	Crankshaft fracture
		Bending	High load	Crankshaft abnormal	Crankshaft vibration abnormal	Damage compressor
		fracture	Crack, High load	shutdown	Shutdown	Severe accident
03	Connecting rod	Crack	Fatigue stress	Crack propagation	Crankshaft vibration abnormal	Connecting rod failure
		Fracture	Fatigue crack propagation	Shutdown	Shutdown	Severe accident
		Small end tile wear	Long-term use, bad lubrication	Running condition variation	Connecting rod failure	Shutdown
		Large end tile wear	Long-term use, bad lubrication	running condition variation	Connecting rod failure	Shutdown
04	Crosshead	Pin wear	Long-term use, bad lubrication	Running condition variation	Crosshead vibration abnormal	Shutdown
		Pin fracture	thermal crack	Shutdown	Shutdown	Severe accident
		Neck fracture	Fatigue stress concentration	Shutdown	Shutdown	Severe accident
		Slip abrasion	bad lubrication	Crosshead vibration abnormal	Crosshead failure	Shutdown
05	Piston rod and piston	Connection loosening	Long-term use, fastening adverse	Cylinder vibration abnormal	Shutdown	Shutdown
		Piston rod fracture	Fatigue crack, stress concentration	Shutdown	Shutdown	Severe accident
		Research on Wear	Long-term use, bad lubrication	Not seal	Cylinder vibration abnormal	Work abnormal
06	cylinder	Crack	stress concentration	Not seal	vibration abnormal	Shutdown
		Inner wall wear	Foreign matter, bad lubrication	Piston ring damage	Leakage	Shutdown
		Oil wiper leaking	Piston rod scuffing	Lubrication oil leaking	pollution	Lubrication oil effect worse
07	Crankcase	Crack	Fatigue , stress concentration	Running condition variation	Crack propagation	Shutdown
		Combustion or explosion	Lubrication oil gasifying	Shutdown	Shutdown	Severe accident
08	Valves	Valve Block damage	Fatigue failure, Friction damage	Work abnormal	Shutdown	Shutdown
		Spring failure	Fatigue failure, Friction damage	Work abnormal	Shutdown	Shutdown
		Leakage	Deformation of valve plate	Work abnormal	Shutdown	Shutdown
		High temperature of exhaust	Exhaust valve leakage, bad lubrication	Valves damage	Shutdown	Shutdown
		Valves product excess carbon	Excess lubrication oil, valves damage	Valves damage	Shutdown	Shutdown

Functional Items	Failure Mode	Risk Level	Maintenance Strategy
Bearing	Loosening	H	condition based maintenance
	Bearing bush abrasion	M	Function testing
Crankshaft	Crack	M	Periodical overhaul/ Replacement
	Bending	M	Periodical overhaul
	fracture	H	Real time state detection
Connecting rod	Crack	M	Periodical overhaul/ Replacement
	Fracture	H	Real time state detection
	Small end tile wear	M	Function testing
	Large end tile wear	M	Function testing
Crosshead	Pin wear	M	Function testing
	Pin fracture	H	Real time state detection
	Neck fracture	H	Real time state detection
	Slip abrasion	M	Function testing
Piston rod and piston	Connection loosening	M	condition based maintenance
	Piston rod fracture	H	Real time state detection
	Research on Wear	L	Corrective maintenance
cylinder	Crack	H	Periodical predictive maintenance
	Inner wall wear	M	Function testing
	Oil wiper leaking	M	condition based maintenance
Crankcase	Crack	H	Periodical predictive maintenance
	Combustion or explosion	H	Real time state detection
Valves	Valve Block damage	M	Replacement
	Spring failure	M	Replacement
	Leakage	M	Replacement
	High temperature of exhaust	M	Replacement
	Valves product excess carbon	M	Replacement

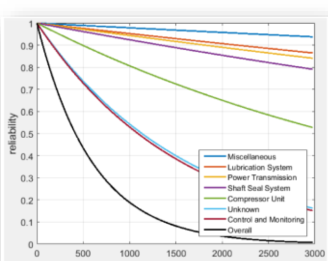
H= High Risk
M= Medium Risk
L= Low Risk

References: (Liang et al., 2012)

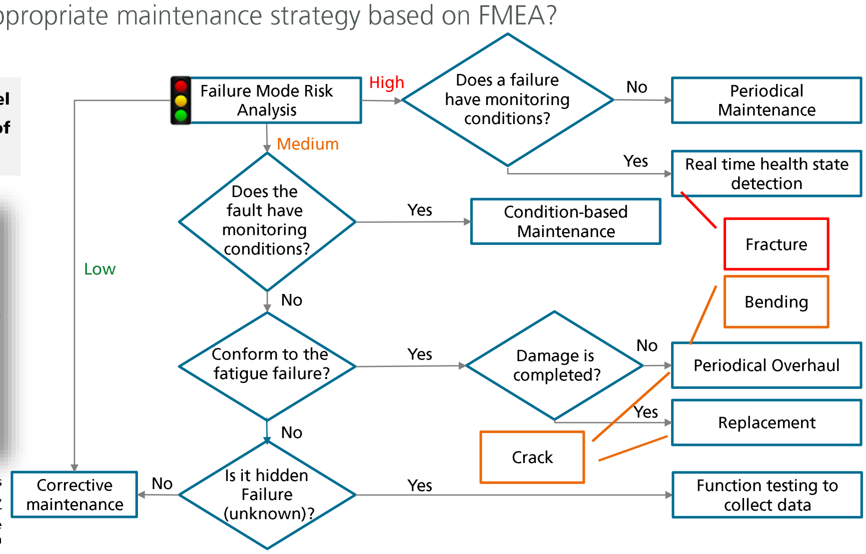
A Procedural Model for Determination of Maintenance Strategy

How do we determine the appropriate maintenance strategy based on FMEA?

- **Next Step** is to identify how to **model and quantify the probability of failure and predict RAM over time.**



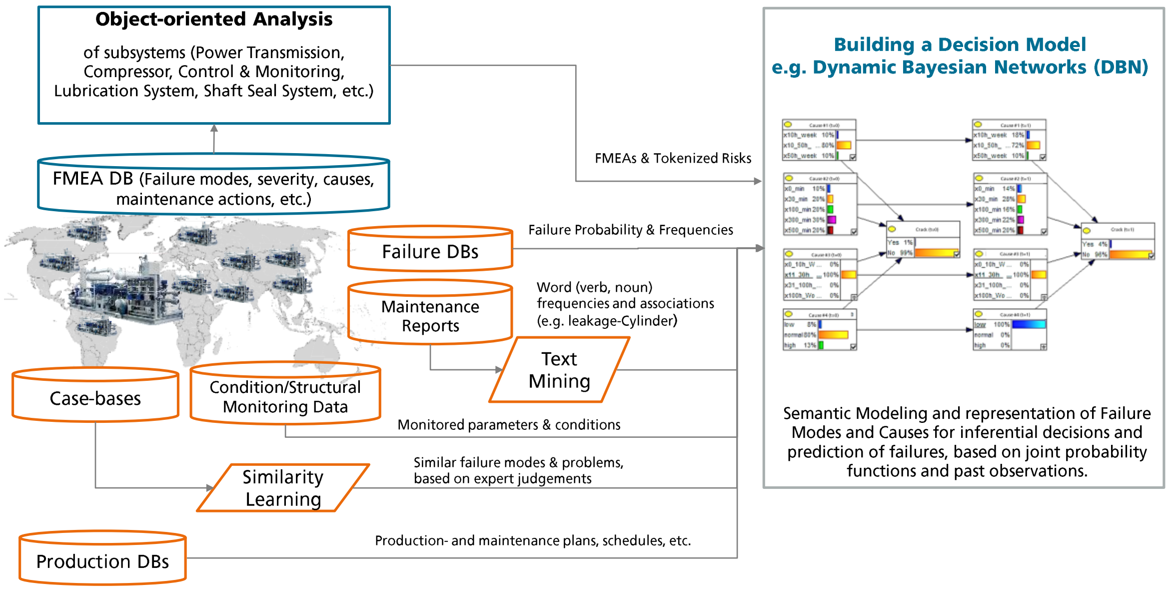
* Determination of appropriate maintenance strategy is based on two main policies: preventive- (periodic, condition-based, etc.) or corrective maintenance (repair and replace), before and after failure moments, which are intended to retain or restore a functional unit in or to a desired functional state.



References: Adopted from (Corvaro et al., 2012), (Spüntrup et al., 2018)

Knowledge-Based Modeling and Analysis of RAM

in Maintenance of Compressor Units – From OEMs and Users Perspectives



What are (Dynamic) Bayesian Networks?

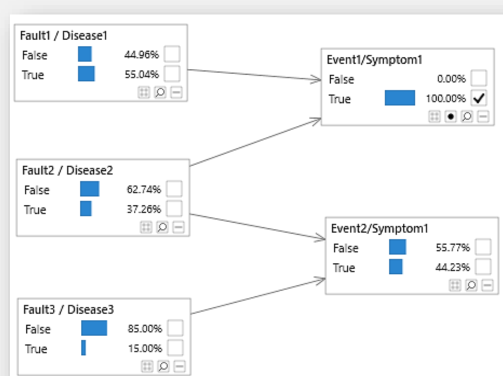
Definition

What are Bayesian Networks (BNs)?

- Bayesian networks are a type of Probabilistic Graphical Model that can be used to **build models from data and/or expert opinion**.
- They can be used for a **wide range of tasks** including prediction, anomaly detection, diagnostics, automated insight, reasoning, time series prediction and decision making under uncertainty.
- They are also commonly referred to as **Bayes nets**, **Belief networks** and sometimes **Causal networks**.

What are Dynamic BNs (DBNs)?

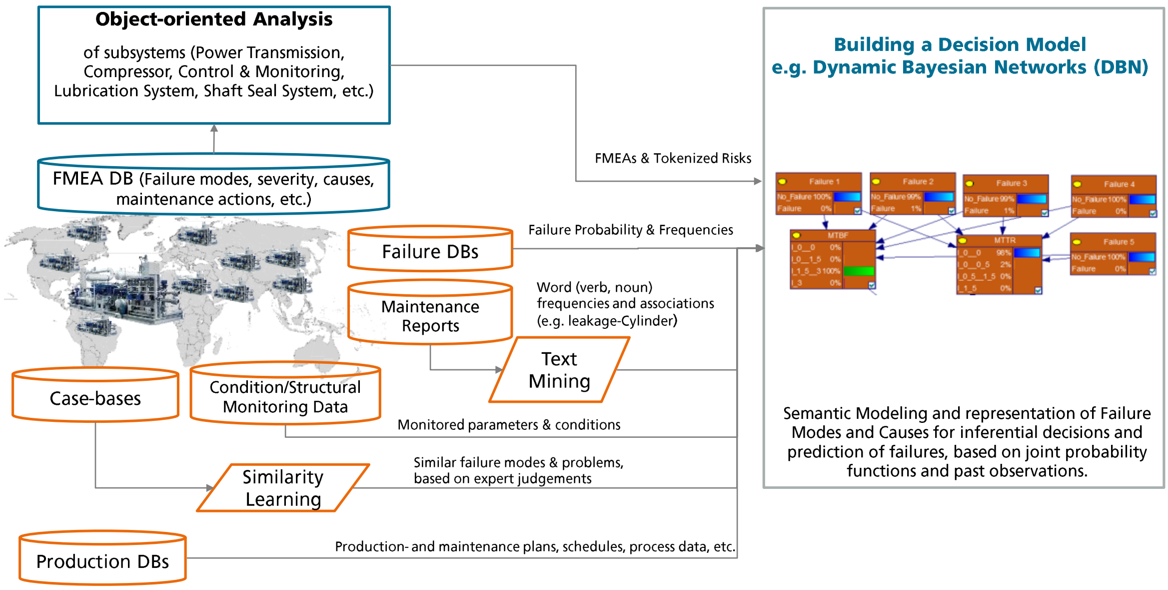
- Dynamic Bayesian networks **extend standard Bayesian networks with the concept of time**.
- This **allows us to model time series or sequences**.
- In fact they can model complex multivariate time series, which means we can **model the relationships between multiple time series in the same model**, and also **different regimes of behavior**, since time series often behave differently in different contexts.



Source: https://www.bayesserver.com/docs/techniques/diagnostics

Knowledge-Based Modeling and Analysis of RAM

in Maintenance of Compressor Units – From OEMs and Users Perspectives



Knowledge-Based Modeling and Analysis of RAM

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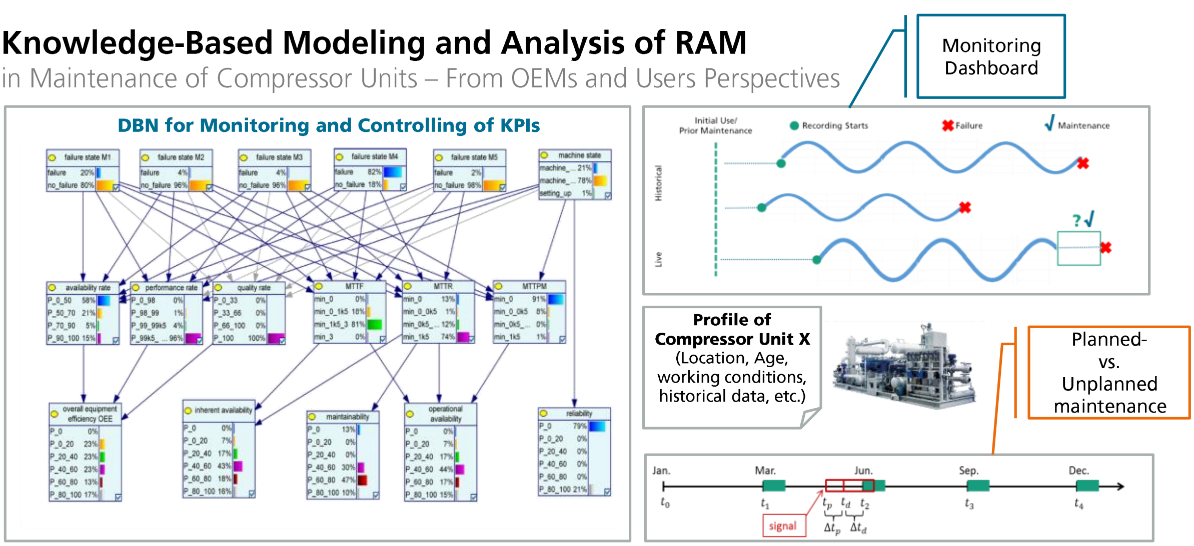

DBN semantically represents FMEA's relations learned from multimodal data, and supports **complex decision-making and prescriptive analytics using RAM's KPIs**

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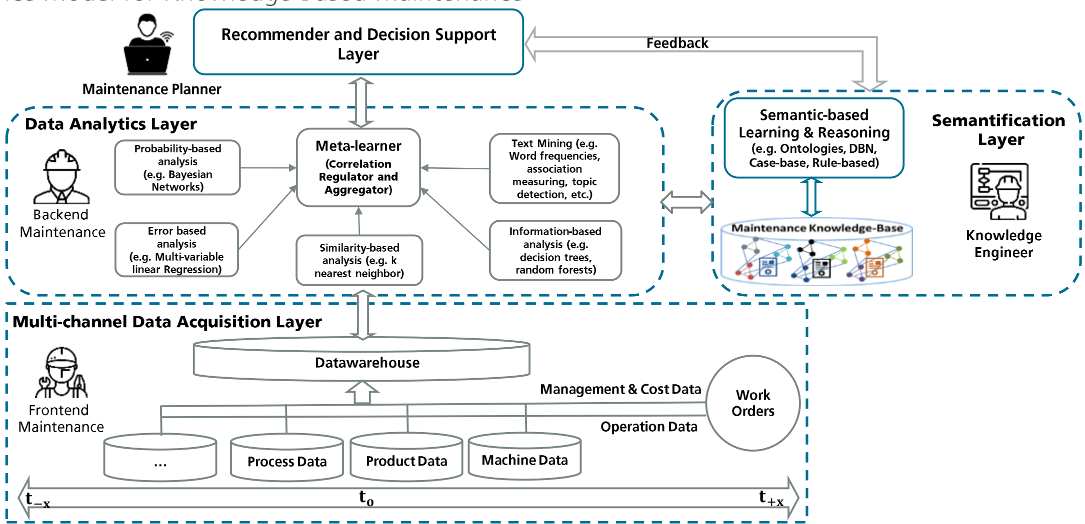
PriMa: Prescriptive Maintenance Model

Reference Model for Knowledge-Based Maintenance



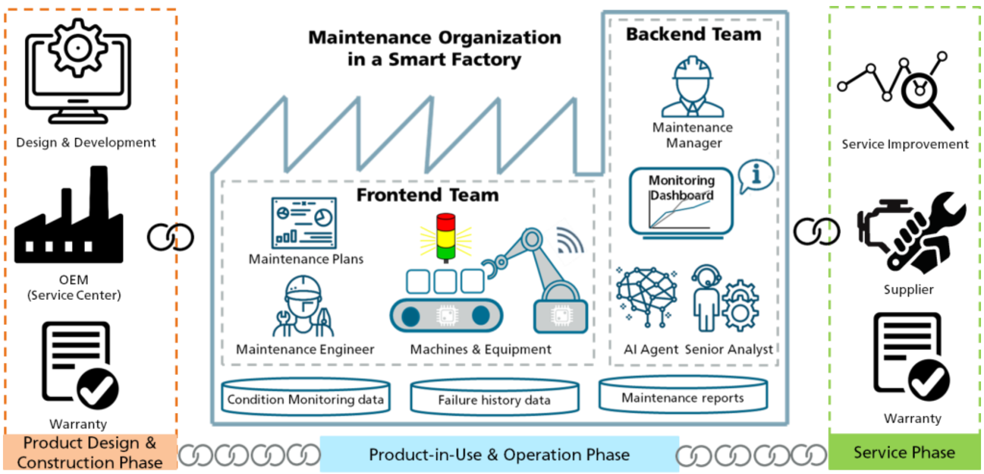
F. Ansari, R. Glawar, & T. Nemeth, PriMa: a prescriptive maintenance model for cyber-physical production systems, International Journal of Computer Integrated Manufacturing, 2019.
F. Ansari and R. Glawar, Knowledge-Based Maintenance, Book Chapter, In Instandhaltungslogistik, K. Matyas (Ed.), 7th Edition, Carl Hanser Verlag, 12/2018, pp. 318-342.

3) Outlook

FUTURE OF KBM: WHERE DOES THE JOURNEY MAY GO IN FUTURE?

Today’s Big Picture of Maintenance

Industrial Maintenance Landscape including OEMs, Operators and Service Suppliers



OEM: Original Equipment Manufacturer

Future of Knowledge-Based Maintenance: Question for Research!

Human-AI Agent Cooperation in KBM

Can a compressor unit itself assist frontend and backend team in maintenance planning and actions?

Human Expert

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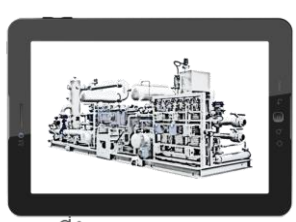

Digital Twin

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Physical Asset

Can a Machine help us maintaining its health score?

Human-AI Agent Cooperation in KBM

Knowledge-Based System in Practice

Knowledge Graph-based Assistance System for Troubleshooting & Documentations

Ansari, F., Hold P., & Khobreh, M. (2020).A Knowledge-Based Approach for Representing Jobholder Profile toward Optimal Human-Machine Collaboration in Cyber Physical Production Systems, CIRP Journal of Manufacturing Science and Technology, Elsevier, Vol. 28, pp. 87-106.

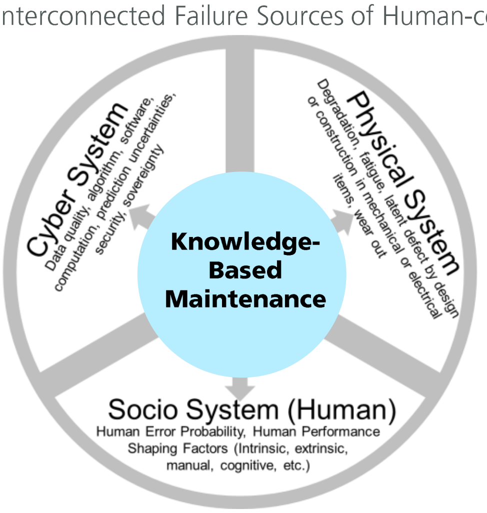
Ansari, F., Kohl, L., Giner, J., & Meier, H. (2021). Text mining for AI enhanced failure detection and availability optimization in production systems. CIRP Annals, 70(1), 373-376.

Project funded by Infineon Technolgies in Austria (since 2020)

To Sum Up

Scientific Challenge: Why Knowledge-Based Maintenance Matters?

Interconnected Failure Sources of Human-centered Cyber Physical (Systems of) Systems



Human-centered Cyber Physical (Systems of) Systems

are more complex and error-prone than

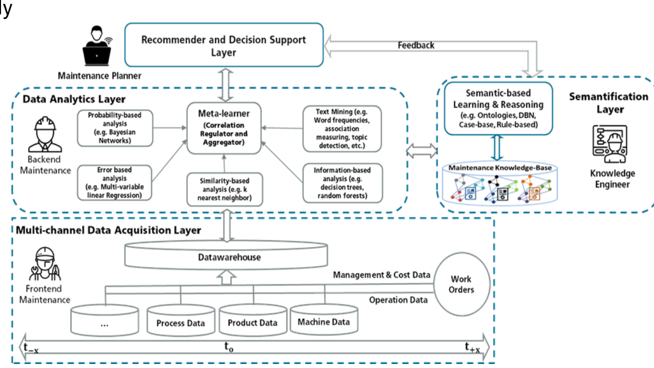
Conventional Human-Machine Systems

F. Ansari, S. Nixdorf & W. Sihn, Insurability of Cyber Physical Production Systems: How Does Digital Twin Improve Predictability of Failure Risk?, 4th IFAC Conf. Advanced Maintenance Engineering, Services & Technologies, Sep. 10-11, 2020, Cambridge, UK **(Winner of Best Paper Award)**

To Bring our Vision of PriMa Model into Reality …

Still we have several challenges in Data Modeling and Analysis in Industrial Context

- **Success of KBM in industrial context** is strongly dependent on
  - Existence of data (e.g. failure data) and evidences (observations)
  - Correctness and validity of data
  - Correct interpretation of data (by algorithms and human)
  - Explainability of algorithm's decision to humans
  - Modeling and incorporation of human knowledge/experiences
  - Employing simulation-based and physics-based models



As we are industrial engineers, on the top of this, we should examine economic and technical plausibility of KBM in each industrial application.

References (1/3)

that help you to learn more about today's lessons – All are Accessible for free via TU's Library

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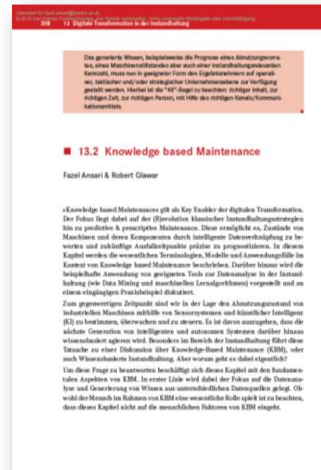
Links are uploaded in TUWEL

References (2/3)

Two Chapters that discuss today's lessons



References (3/3)

Read and Listen

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Q&A?

- **Any question so far?**
- **Next Lecture: 02.05.2023**
- **Topic of Next Week:**
  Knowledge Representation (Ontologies/Knowledge Graph)

Technology for People!

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