Autonomous operation

MAN Energy Solutions
Future in the making

Digital tools for more efficiency in turbomachinery

List of standard abbreviations

cf.	confer (compare)
e.g.	exempli gratia (for example)
et al.	et alii (and others)
fig.	figure
i.e.	id est (that is)
p.a.	per annum
tab.	table

List of technical abbreviations

AI	Artificial intelligence
CAPEX	Capital expenditure
EPC	Engineering, procurement, and construction
FEED	Front-end engineering design
MPC	Model predictive controller
HMI	Human-machine interface
OPEX	Operational expenditure
PLC	Programmable logic controller
RL	Reinforcement learning
SAE	Society of Automotive Engineers
TBO	Time between overhauls
TOTEX	Total expenditure

Synopsis

This document gives a broad overview of the historical development and current status of autonomous operation of turbomachinery plants with references and comparisons to the automotive industry and industrial production.

The authors examine the rationale and objectives of autonomous operation, describe the digital tools currently in use, and necessary developments, as well as the required paradigm change in the industry with regard to TOTEX.

This white paper describes the roadmap to autonomous operation for applications in the turbomachinery industry and presents a basic introduction to the essential concepts, experiences, expertise, and tools in a condensed form.

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Defining the levels of autonomy

Automatic components regulated the water clocks of the ancient Greeks. They enabled the industrial revolution. Science fiction gave us self-controlling robots. But the taxonomy of autonomy was defined by the car.

Automotive industry

The term “autonomous driving” refers to the highest level of automation (level 5: full automation). Back in 2014, SAE International published definitions of the autonomy levels for the first time (cf. SAE International, 2014). The latest update with precise definitions has also been brought into alignment with the ISO Technical Committee (PAS 22736), both of which were published in 2021. Level 2 (partial automation) is currently the technical standard in the automotive industry worldwide. SAE level 3 (conditional automation) is already technically possible today and was officially (partly) approved as standard in 2021. At level 3, the driver only intervenes when prompted by the system. At the highest level of autonomy, level 5, no driver intervention is necessary. The vehicle steers safely to its destination in all traffic situations.

Level	Definition	What does it mean for the automotive industry?
0	No automation	The human driver performs all aspects of the dynamic driving task at all times.
1	Driver assistance	A driver assistance system performs either steering or acceleration/deceleration depending on the driving mode.
2	Partial automation	One or more driver assistance systems perform both steering and acceleration/deceleration occasionally or depending on the driving mode. The human driver performs all other aspects of the dynamic driving task.
3	Conditional automation	An automated driving system performs all aspects of the dynamic driving task depending on the driving mode. The human driver has to respond appropriately to a request to intervene.
4	High automation	An automated driving system performs all aspects of the dynamic driving task. The human driver does not have to respond to a request to intervene.
5	Full automation (autonomous driving)	An automated driving system performs all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.

Tab. 1: Simplified “Levels of Driving Automation” Standard for Self-Driving Vehicles

Industrial production

The five levels of autonomy have been adapted from the vehicle industry. Level 5 (autonomous operation in all areas) means that no human input is required at all. The standard at present is level 2 to 3.

Level	Definition	What does it mean for industrial production?
0	No automation	The operator has full control without assistance.
1	Assistance with selected functions	The operator is always responsible and makes all decisions.
2	Occasional autonomy in clearly defined areas	The operator is always responsible and assigns (partial) objectives.
3	Limited autonomy in larger sub-areas	The system issues a warning in the event of problems; the operator confirms the solutions suggested by the system and has a recourse function.
4	The system operates autonomously and adaptively	Within specific system limits; the operator can monitor or take action in an emergency.
5	Autonomous operation in all areas	Including cooperation and within varying system limits; the operator can be absent.

Tab. 2: Simplified technology scenario: Artificial intelligence in Industry 4.0

Turbomachinery

In 2017, MAN Energy Solutions established an expert group on autonomous operation to apply the definition of autonomous operation to the world of turbomachinery and to identify the developments that are necessary. Around the world, modern turbomachinery systems are highly developed in terms of autonomy levels. Level 3 (high automation) is already the technical standard for turbomachinery systems. And in some market segments, such as subsea applications, turbomachinery systems can already be operated at level 4, i.e. remotely controlled and unmanned. Only if the process control system detects an anomaly will the equipment switch to a safety mode and will the operating personnel take over.

The core of the highest autonomy level (level 5) for process plants with turbomachinery will be unmanned and energy-efficient operation.

In addition to safe, unmanned operation, the significant added value of autonomous operation of turbomachinery is thus the safeguarding of energy efficiency.

Level	Definition	What does it mean for turbomachinery?[1]
0	Human operation	The operators operate the machine train/asset themselves (start up, shut down, speed control, pressure control, performance control, etc.).
1	Assistance	Certain assistance systems help the operators with operation (surge detector, surge controller, speed controller, etc.); installed sensors help to monitor important parameters in the control room.
2	Partial automation	Automatic systems for transient conditions (start up, shut down) and continuous operation (surge control, speed control, load sharing, etc.); a large number of sensors helps to monitor important parameters in the control room.
3	High automation	Operation and monitoring of the machine train/asset is centralized from the control room. Automated machine and process monitoring. The machine train/asset automatically performs functions such as start up, shut down, load changes, continuous operation. (This level is technical state of the art today.)
4	Full automation	No operating crew permanently required on site/at the asset (unmanned operation). If the control system indicates failures/anomalies, the machine train is automatically switched to safe operation mode; the operators have to take the lead in evaluation and action. (This level is technically feasible today.)
5	Autonomous operation	The management of the machine train/asset is permanently taken over by the control and remote diagnostic system using advanced analytics with real-time data-based self-diagnostic system. Digital maintenance and performance management system with anomaly detection and failure prediction, remaining useful lifetime calculation, prognostic maintenance, energy-optimized performance/lifetime balance management. Human intervention only in the case of condition-based maintenance.

Tab. 3: Internal expert brainstorming results relating to autonomous operation

[1] At present, no official international definitions of levels exist for turbomachinery plants.

Targets and benefits of increasing autonomous operation

The motivations that drive the development of autonomous operation do not differ greatly for each industrial segment and their respective stakeholders. The benefits range from reducing accidents to raising efficiency and improving sustainability.

Automotive industry

In the automotive industry, one of the biggest motivations for autonomous driving is the avoidance of potential human errors and thus the reduction of traffic accidents through unmanned driving.

According to statistics, approximately 1,210,000 people die behind the wheel each year. Almost 3,500 people die every day in traffic accidents and almost 50 million are injured or survive with a disability.

Since accident statistics are also evaluated in relation to specific brands, manufacturers are naturally very interested in enhancing their reputation and thus their competitiveness in the market through safe everyday driving. However, the introduction of higher autonomy levels in very dynamic road traffic is not only a complex technical issue, but also a difficult ethical and legal one. In stress testing, the criterion of ethics must always be the top priority. This means that health always comes before reaching the finish line quickly.

Target date: The vehicle industry has set a goal of ensuring **level 4** high automation by 2025.

Country	Fatalities per 100,000 inhabitants					Fatalities per billion vehicle kilometers				
	1970	1980	1990	2000	2009	1970	1980	1990	2000	2009
Australia	30.4	22.3	13.7	9.5	6.8	49.3	n/a	n/a	9.3	6.7
Austria	34.5	26.5	20.3	12.2	7.6	109	56.2	27.9	13.2	9
Belgium	31.8	24.3	19.9	14.4	8.9	105	50.0	28.1	16.3	9.6
Canada	23.8	22.7	14.9	9.5	6.3	n/a	n/a	n/a	9.3	6.3
Czech Republic	20.0	12.2	12.5	14.5	8.6	n/a	53.9	48.3	37	19.4
Denmark	24.6	13.5	12.4	9.3	5.5	51	25.0	17.3	10.7	8.2
Finland	22.9	11.6	13.1	7.7	5.2	n/a	20.6	16.3	8.5	5.2
France	32.6	25.1	19.8	12.9	6.8	90	43.6	25.7	15.1	7.8
Germany	27.7	19.3	14.0	9.1	5.1	n/a	37.3	20.0	11.3	6.0
Greece	12.5	15	20.1	18.7	12.9	n/a	n/a	n/a	n/a	n/a
Italy	20.5	16.4	12.6	12.2	7.1	n/a	n/a	n/a	n/a	n/a
Japan	21.0	9.3	11.8	8.2	4.5	96	29.3	23.2	13.4	7.7
Korea	n/a	17.2	33.5	21.8	12	n/a	n/a	n/a	49.5	20.2
Netherlands	24.6	14.2	9.2	6.8	3.9	n/a	26.7	14.2	9.1	5.6
New Zealand	23.0	18.9	21.4	12.1	8.9	n/a	n/a	n/a	12.4	9.6
Norway	14.6	8.9	7.8	7.6	4.4	n/a	19.3	12.0	10.5	5.4
Poland	10.6	16.8	19.2	16.3	12	n/a	n/a	n/a	12.4	9.1
Spain	n/a	17.7	23.2	14.5	5.9	n/a	n/a	n/a	n/a	n/a
Sweden	16.3	10.2	9.1	6.7	3.9	35	16.4	12.0	8.5	4.4
Switzerland	26.6	19.2	12.9	8.3	4.5	56.5	30.9	18.5	10.4	5.7
United Kingdom	14.0	11.0	9.4	6.1	3.8	n/a	n/a	n/a	7.4	4.6
United States	25.8	22.5	17.9	15.3	11.1	29.7	20.9	12.9	9.5	7.1

Tab. 4: Excerpt from WHO statistics: Number of people dying in traffic accidents worldwide

Industrial production

In industrial production, one of the biggest motivations for autonomous operation is the avoidance of potential human errors and thus the reduction of production failures as well as serious accidents.

Especially for the globalized operators of complex industrial plants, it is becoming more and more difficult to guarantee the plant personnel's high standard of technical expertise in 24/7 operation due to demographic changes, internationalization, and the increasing remoteness of operating sites.

The coronavirus pandemic that took hold in 2020 and the associated limited global availability of experts due to lockdowns and travel restrictions have further exacerbated this shortage.

The goal is unmanned, remotely monitored operation – or, as a first step, a 50 % reduction in operating personnel.

Other key drivers of autonomy in industry are, of course, economic aspects such as:

- Speed
- Flexibility
- Cost efficiency
- Increased resilience in crises

Plant availability and production efficiency are key cost factors. In this context, energy balance is increasingly becoming a catalyst for the development of autonomous operation as part of companies' decarbonization strategies. As in the automotive industry, the focus of modern industrial production must always be on protecting the entire environment, i.e. people, equipment, and nature.

Target date: The industrial sector expects to achieve **level 5** autonomy before the end of this decade, i.e. by 2030 at the latest.

Turbomachinery

The operators of turbomachinery plants have the same motivations for the development of autonomous operation as industrial producers.

A 0.2 % improvement in the availability of a machine plant in different market segments results in various positive financial effects as shown in the business cases calculated by MAN Energy Solutions (Tab. 5).

According to the business cases calculated by MAN Energy Solutions (Tab. 6), a 50 % reduction in the field staff of a machine plant (near-unmanned operation) results in various positive financial effects in different market segments.

However, the greatest positive financial effect is for energy efficiency. Here, an increase of just 1 % results in positive financial effects of > €2,000,000 per year. This explains the high motivation for autonomous operation.

Authors' note: Because of the enormous importance of energy savings, there will be an overlapping transition from level 4 to level 5 in the turbomachinery industry. This will be expressed in intermediate developments such as "semi-autonomous" or "near-autonomous".

The advantage is that the operators of turbomachinery plants can enjoy the benefits both of minimally manned or unmanned operation plus energy-efficient operation even before the autonomy level 5 is reached in its final stage.

Since 2021, MAN Energy Solutions has been able to support customers with near-autonomous operation in all market segments and is aiming to achieve level 5 (fully autonomy) for all turbomachinery equipment by 2028 at the latest. This means maximum uninterrupted, normally unmanned, safe, reliable, and energy-efficient operation.

Market segment	Additional operating profit p.a.
Industrial gases	Up to € 200,000
Refinery	Up to € 500,000
Basic industries	Up to € 700,000
Upstream oil and gas	Up to € 1,000,000

Tab. 5: Availability increase: Positive gross profit effect in calculated business cases

Market segment	Additional operating profit p.a.
Industrial gases	Up to € 100,000
Refinery	Up to € 400,000
Basic industries	Up to € 400,000
Upstream oil and gas	Up to € 200,000

Tab. 6: Near-unmanned operation: Positive gross profit effect in calculated business cases

Target date: MAN Energy Solutions aims for **level 5** autonomous operation for all turbomachinery equipment by 2028 at the latest.

Defining autonomous operation in turbomachinery plants

We need clear concepts of what automation can achieve in order to help us manage the increasing complexity of turbomachinery plants and their integration in global supply chains.

Translated into the industrial application of turbomachinery plants, autonomous operation of turbomachinery equipment is defined as follows:

- Decisions on train operation (process setpoints) with regard to yield, efficiency, emissions, actual market price, and energy costs, process stability, alarms, maintenance demand, etc. in order to maximize asset utilization
- Maintenance management with anomaly detection and failure prediction, remaining useful lifetime calculation, prognostic maintenance
- Digital self-diagnostic system with advanced real-time database analytics
- Performance management with energy optimization, performance/lifetime balance management
- The management of the asset is permanently taken over by the remote diagnostic and control system
- Human intervention only in the case of prescriptive maintenance

(cf. MAN Energy Solutions 2019)

Modern digital solutions

The tools for promoting autonomous operation are identical across industries. They have one thing in common: They are digital solutions developed with the help of the human expertise of specialists.

The human factor

While the authors have defined and promoted autonomous operation by bridging the gap between the automotive industry and the world of turbomachinery, the following section draws an analogy between humans and turbomachinery.

In the industrial world, it is common to speak of artificial intelligence (AI) and digital twins. Essentially, five main categories of modern digital solutions are interlinked in autonomous operation.

Online diagnostics

Just as modern medical diagnosis is able to monitor a person's health and energy balance around the clock, modern online machine diagnostics are now able to monitor the health and energy balance of machine equipment around the clock, regardless of time zones and distance.

Advanced digital solutions are already available today, increasingly including AI solutions and digital twins for online health and energy balance diagnostics, e.g. online analytics of steam, lubricating oil, vibrations, acoustics, gas composition, energy efficiency, etc.

Thanks to very fast data sampling rates and high data transmission rates, almost real-time monitoring is already technically possible today.

In addition, thanks to modern algorithms, it is already possible to precisely predict the health status of the machine systems with increasing observation periods.

Digital twins

There is no such thing as a single digital twin, but rather there are many individual digital modules, each of which has a different function and thus value, and which, when combined, represent a digital twin. Digital twins are used to simulate very complex turbomachinery systems and their behavior by means of artificial intelligence, allowing the equipment to be optimized even before it is put into operation. Current state-of-the-art digital twins include, for example, dynamic simulations, virtual sensors, virtual commissioning, and training simulators.

Dynamic simulation

The main objective of a dynamic simulation study is to examine the dynamic interaction between all equipment components in order to confirm operation under a number of defined procedural and upset conditions. The simulation model makes it possible to evaluate the design and identify potential problems.

Performance monitoring app

Software module for calculating efficiency deviations for all operating points, AI-based algorithm, integrated PLC software including HMI and alarm function; training data is gathered from the simulation model.

Operator training simulator

The operator training simulator uniquely combines the original automation software with an authentic dynamic simulation model simulated in real time. This approach is based on the long-standing, proven principle of virtual commissioning using a software-in-the-loop coupling, where the plant response is simulated using the dynamic simulation model in the framework, and the physical PLCs are replaced by emulated virtual controllers.

Virtual commissioning

Virtual commissioning includes the real-time dynamic simulation model with, for example, compressor units, suction and discharge systems, interconnected piping, steam turbines or electrical drives, and auxiliaries. The control system with original project software and HMI will be connected to the simulation model using real and virtual signal bus interfaces. This setup allows comprehensive testing and optimization of the software and precise configuration of the controller parameters before the actual commissioning of the equipment.

Virtual sensors

Virtual sensors are software sensors (based on neural network technology), which normally run in parallel to physical sensors and generate output signals based on defined input signals from physical sensors. The main objective of virtual sensors is the prevention of spurious trips caused by damaged physical sensors as non-intended process shutdowns, resulting in higher asset availability. Virtual sensors can be provided for most measurements which are relevant to equipment shutdown, alarms or control functions.

Remote services

The top five most essential state-of-the-art remote services are:

- Remote real-time condition monitoring
- Remote access
- Remote inspection
- Remote commissioning
- Remote troubleshooting

In the past, operators in particular were often skeptical and hesitant about remote services, but the COVID-19 pandemic has significantly increased their confidence. Remote commissioning in particular has become more important since the COVID-19 pandemic and, due to the lockdowns and associated travel restrictions, has had to develop very quickly.

In April 2020, MAN Energy Solutions successfully carried out remote commissioning (including mechanical completion, cold commissioning, and hot commissioning) of a nitric acid plant in Uzbekistan for the first time (cf. MAN Energy Solutions 2020).

Just two years ago, it had never been done before, but today it is a very good alternative, as the technology, expertise, and contract modules are mature.

The growing importance of remote commissioning is also underlined by the fact that the VDMA published a guideline for this in September 2021 (cf. VDMA 2021).

In 2022, MAN Energy Solutions therefore added remote commissioning to its product range as a standard service package.

Thanks to high transmission rates via cable or satellite, the best encryption technologies, and cloud-based solutions, remote services have become the “new standard” in the era of lockdowns and the associated travel restrictions.

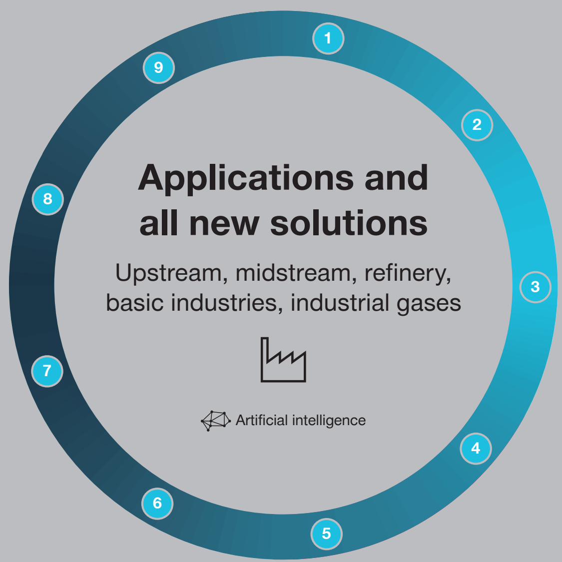
The tools shown in Fig. 1 are a “must-have” to achieve remote operation. Without mastery of these tools, it is not possible to reach the next stages of development toward autonomous operation.

And it is also clearly apparent that these tools require a combination of high-level digital and human expertise.

Fig. 1: Overview of digital solutions

MAN turbomachinery digitization

1. Cyber security
2. Dynamic simulation
3. Virtual commissioning
4. Operator training simulator
5. Virtual sensors
6. Simulation-based control software FAT
7. Performance monitoring apps
8. Online oil and steam quality monitoring
9. Remote services



Data and cyber security

All digital solutions must meet data and cyber security requirements. The highest standards have been developed and refined in the industry for this purpose, and they must be consistently and preventively complied with.

The multi-level concepts with the defense in depth principle must be continuously developed through regular hackathons as stress tests and proof of data and cyber security. Data and cyber security are absolutely essential to earn the trust of operators of highly complex industrial plants in autonomous operation.

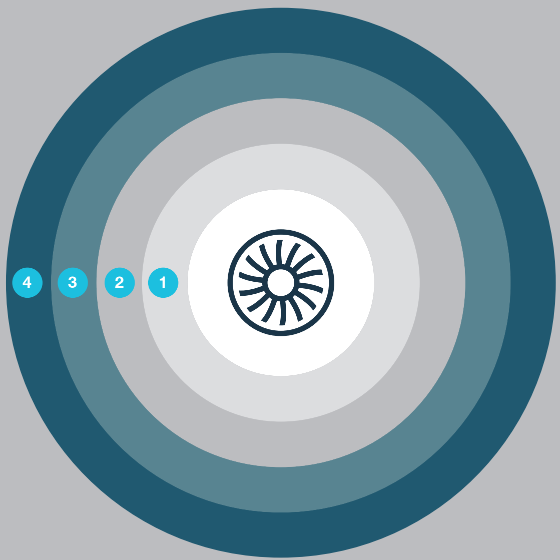
Robotic surveillance

Like a family doctor, a trained expert in the plant can detect changes with their own senses – e.g. leaks, noise changes, and vibration changes – that indicate a negative trend in the health of the machinery, even without machine diagnostics. In the case of unmanned operation, remote monitoring of changes in operation with digital sensory organs is of great importance. Here, modern digital technologies such as drones and patrol robots are used. These are equipped with appropriate sensors, record trends, and send messages as soon as changes occur (e.g. increased noise levels, leaks, etc.). Robots thus complement field personnel in a positive sense.

Fig. 2: Multi-level "defense in depth" principle

Cyber threats internally and externally

1. Component security
2. Network security
3. Plant security
4. Organizational security



AI for safe and reliable operation

Looking back, it can be said that the state of the art has already reached a considerable level nowadays. Looking into the future, however, it becomes clear that the importance and the proportion of AI solutions will increase significantly.

Latest developments

AI solutions, such as maintenance management, machine learning, reinforcement learning controllers, performance management, etc., are being advanced.

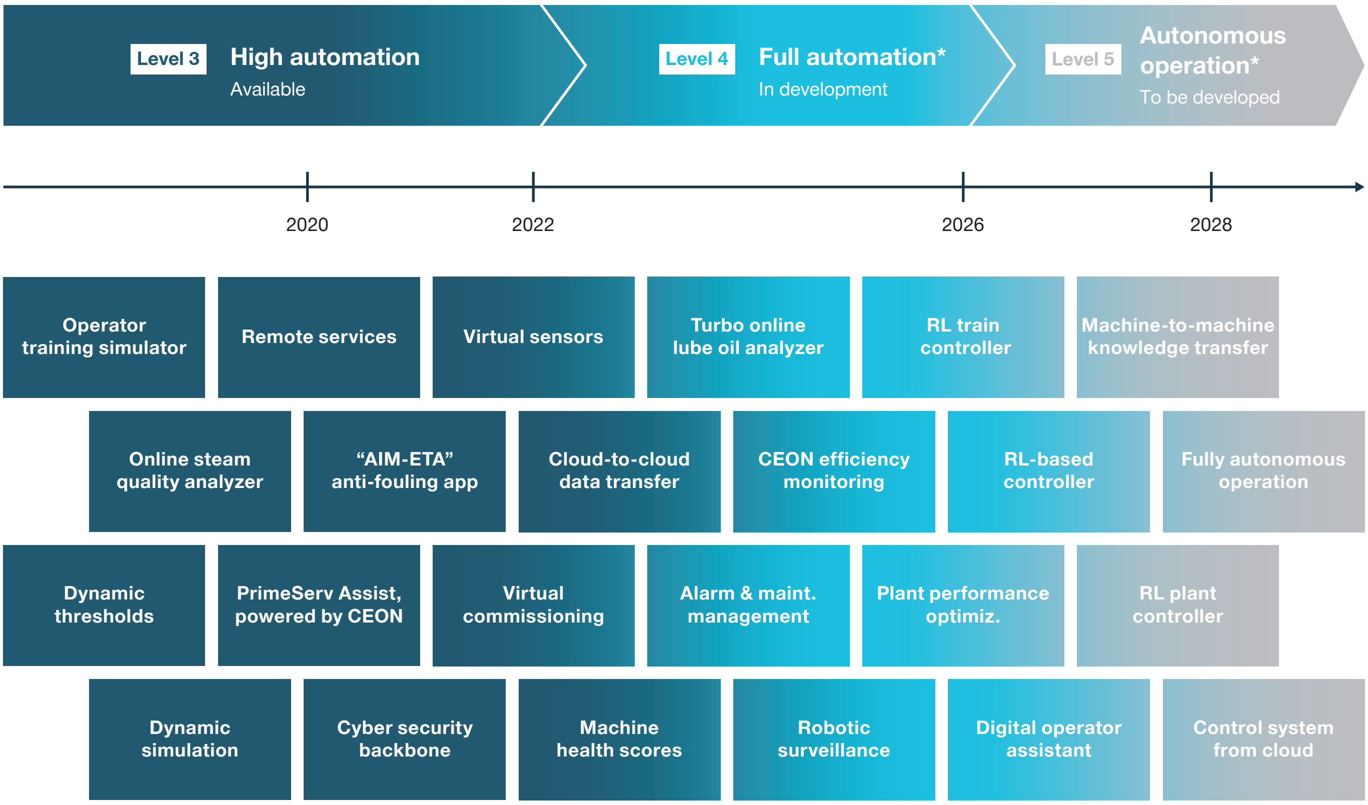
Interaction between the digital solutions that are already available – and those currently under development – will enable the safe and reliable autonomous operation of turbomachinery systems in the future.

Future AI-supported maintenance management will revolutionize the philosophy of maintenance by enabling prescriptive maintenance. With high-resolution real-time operational data monitoring and advanced analytics, not only can the health status of the equipment be monitored 24/7, but reliable long-term forecasts can also be calculated. Similar to weather forecasting, where global online data collection and calculation models make long-term forecasting increasingly precise, it is now possible to predict necessary maintenance activities for machinery. As a result, planned maintenance intervals can be significantly extended and maintenance activities that become necessary can be proactively tackled.

The latest – and most notable – AI category in the development of autonomous operation is the AI-based model predictive controller (MPC): This solution is based on a combination of reinforcement learning technology and first-principle modeling, which calculates holistic control actions by solving an optimization problem in real time, taking account of energetic conditions, maintenance demand, market prices for the product, energy costs, etc.
In the simulation environment, the mathematically described punishment and reward additionally teach the controller to master complex transient process operations such as process start-up. The solution trained by several tests on the model is transferred to the controller and immediately ensures proper operation the first time it is used. In continuous use, the controller continues to learn the real operation and improves further.

Modern digital tools	Achievable time between overhauls (TBO)
Without	Standard (3 years to max. 5 years)
24/7 online health monitoring	Min. 5 years, up to 8 years possible
24/7 online health monitoring and AI-based maintenance management	Min. 6 years, up to 12 years possible

Tab. 7: MAN Energy Solutions SE statistics and experience



* With further developments using artificial intelligence

Fig. 3: Roadmap and “digital diamonds” for autonomous operation by 2028, first timeline created in November 2019

Requirements for a paradigm shift

Essential digital solutions are already available today that enable unmanned, or even near-autonomous, operation of turbomachinery systems, while further digital modules are being developed to achieve the goal of autonomous operation.

Four factors of change

The turbomachinery industry has to rethink four essential points with the goal of achieving the optimal combination of human expertise and artificial expertise.

Expert alliances

The first criterion for the necessary paradigm shift is the formation of expert alliances.

Transferred to the industrial world of turbomachinery, this means that turbomachinery systems are always embedded in complex industrial plants. **Consequently, autonomous operation requires an in-depth understanding of:**

- Industrial process
- Core machines and process equipment behavior
- Modeling and simulation
- Classical automation
- AI-based control technologies

It is becoming increasingly difficult for all parties involved to master this expertise in its entirety on their own. Successful autonomous operation thus requires a shift in thinking from the classic customer/supplier relationship to alliances based on partnership and mutual trust, in which each chosen partner contributes their best specialist expertise, thus creating significant added value in terms of knowledge.

If the first step is the formation of partnerships between customers and suppliers based on mutual trust, then the next step is the mutual provision and use of real-time data, naturally in compliance with the strictest data and cyber security requirements.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Digitalization cooperation: MAN Energy Solutions and thyssenkrupp to work on autonomous operation of turbomachinery

Digitalization cooperation: MAN Energy Solutions and thyssenkrupp to work on autonomous operation of turbomachinery

- MAN Energy Solutions and the thyssenkrupp business unit Uhde to use AI to conserve resources and boost efficiency
- Autonomous operation of compressor trains for nitric acid plants and other applications

Fig. 4: Joint press release by thyssenkrupp Industrial Solutions AG (thyssenkrupp Uhde) and MAN Energy Solutions SE in June 2021 regarding alliance to develop autonomous operation in nitric acid applications

Remote first

The second criterion required in the industry's rethinking concerns remote first. That is, the availability, sharing, and processing of real-time data for secure data read access as well as secure remote access (if needed) for troubleshooting.

The philosophy of distributing expertise among the partners with the best knowledge and a remote first approach achieves an outstanding level of efficiency in a globalized world equipped with digital solutions.

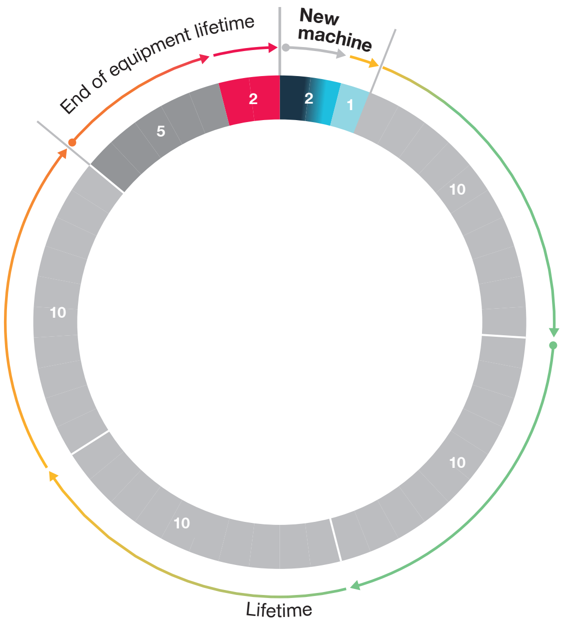


Fig. 5: Average life cycle of turbomachinery equipment

TOTEX

The third criterion required in the industry's rethinking is the change from considering capital expenditure (CAPEX) and operational expenditure (OPEX) separately to considering TOTEX holistically.

In the holistic TOTEX assessment, the entire life cycle of a turbomachinery system is taken into account from the early FEED phase onward and equipped with digital solutions.

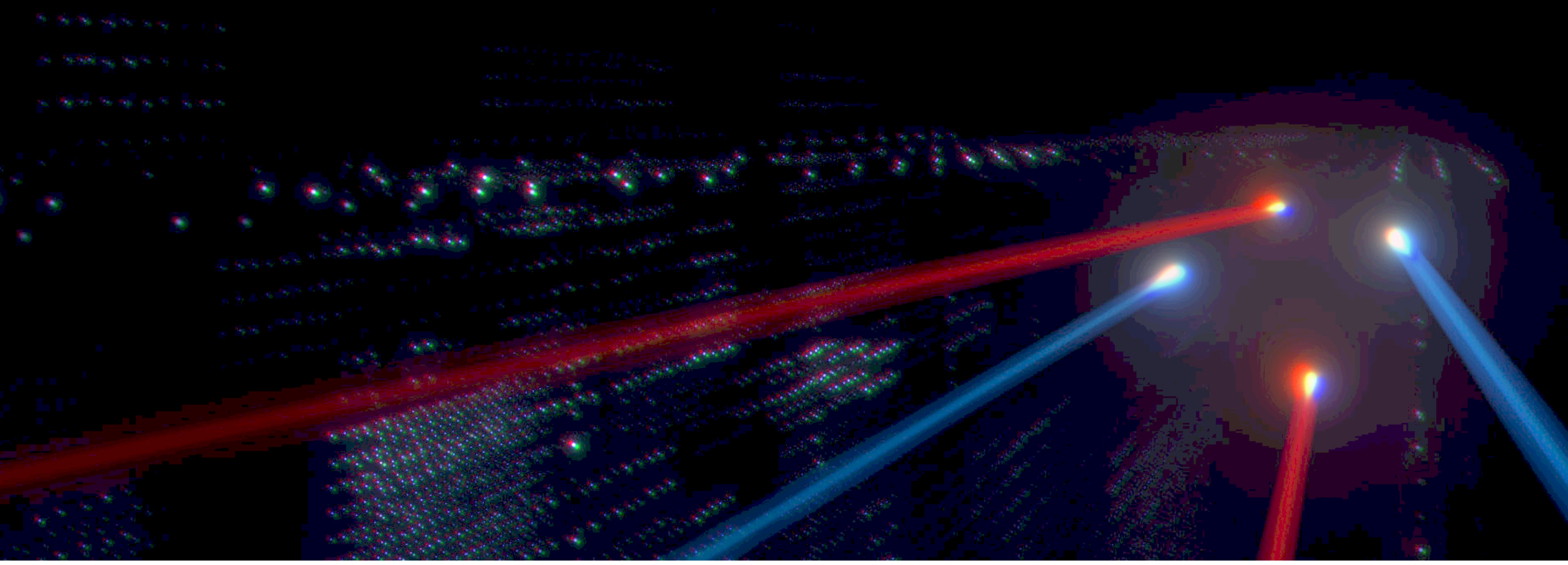
A turbomachinery system has a long service life, often reaching or even exceeding 50 years. The TOTEX approach examines the costs of the pure initial investment and the costs during operation of the machine plant over a long observation period of at least 15 to 20 years.

If an investor wants to ensure safe, unmanned, minimally interrupted, consistently energy-efficient operation of their plant, the engineering, procurement and construction (EPC) will have a greater role in the future. This is because having the foresight to intelligently consider TOTEX leads to useful digital solutions being included from the beginning, i.e. as early as in the CAPEX phase. If an investor in a greenfield plant is interested in future autonomous operation of the plant, is ready for a paradigm shift, and wants to implement the philosophy of expert alliances, remote first, and TOTEX consideration, then they pave the way for "design for digital" of their plant.

Design for digital

The digital life cycle of a greenfield industrial plant with turbomachinery and the goal of future unmanned, and also autonomous, operation begin with a holistic TOTEX approach in the early phase, during conception and specification. This approach is used to design the entire digital life cycle of a machine plant.

In future, design for digital in autonomous operation will probably move toward the humanization of machine systems. This means that the turbomachinery system communicates linguistically with the operators and provides accompanying information on the condition, the selected operating, and upcoming maintenance work.



Digital solutions along the project life cycle

In line with the philosophy of a digital life cycle, digital modules are recommended in each of the project phases, and it is advisable that these be taken into account at the early stage of the tender.

Proposal for a digital life cycle

This means, when designing plants with turbomachinery for safe unmanned – or even autonomous – operation, modern digital solutions are safeguarding the entire equipment from the beginning to the end of the service life. So what does a digital life-cycle solutions suite contain for the entire digital life cycle? The following is a brief list of what the authors consider to be recommended digital modules in the respective project phase as part of design for digital.

Project phase	Digital modules
FEED	- Cyber security concept - Dynamic simulation - Remote access connectivity
Engineering and manufacturing	- Virtual sensors - Virtual commissioning - Online monitoring system - Operator training simulator
Commissioning and operation	- Advanced analytics - Robotic surveillance - Remote access - Remote collaboration - Machine learning - AI-based maintenance management - Reinforcement learning (RL) controller

Tab. 8: Modules of an ideal digital suite

Conclusion

The crisis caused by the COVID-19 pandemic has promoted the development of digital solutions with the aim of autonomous operation.

In addition to safe, unmanned operation, the significant added value of autonomous operation of turbomachinery is its energy efficiency. Current developments show that autonomous operation of turbomachinery equipment will be feasible by 2028 at the latest.

In order to follow this roadmap, the further development of AI-based solutions, such as reinforcement learning, maintenance management, and performance management, will be promoted. And a paradigm shift is required with regard to expert alliances, remote first, the TOTEX approach, and design for digital.

The authors recommend that investors in greenfield industrial plants with turbomachinery equipment who are interested in operating the entire plant unmanned or autonomously focus on a digital life-cycle concept from the earliest stage in the project.

Finally, the authors emphasize that autonomous operation of machinery with turbomachinery equipment will not replace human personnel and the expertise they offer. Rather, the combination of human expertise and AI expertise is the key to success.

Figures

Tables

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