How Software keeps your Wind Tunnel up to date for Efficiency and new Use Cases

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Abstract: Usually, wind tunnels have a supervisory control system originally installed. However, just like subsystems, the supervisory control system will "age" as new requirements come up. For some time, it might be possible to add functionality or to develop adjacent systems for certain tasks at rising cost. However, at some point it is just time to replace the system reaching its limits. Then, minimal downtime and minimal changes to subsystems to not involve all different (maybe even no longer available) suppliers is the goal. Thus, an ideal solution would be a modular and configurable system by a proven IT-integrator that can adapt to the present subsystem interfaces and their behaviors. Simultaneously, the new system shall avoid running into such obsolescence situations quickly again. Thus, it should offer a lot of configuration options and modularity to allow for future changes. We present a NoCode/LowCode-concept based on our platform WTCS, suitable for upgrades with minimal downtimes (actual parallel operation with the old system in many situations), and massive adaptability and future-readiness by modularity. From a self-installable base set, over customer-usable configuration editors for interfaces, test sequencer environment and ISO17025-compliant test management, to user-defined user interfaces, the system allows for various project situations from full-service projects to almost exclusive customer-executed implementation after corresponding training.

1 Introduction

When building a wind tunnel, the necessity of regular mechanical, electrical or hydraulic maintenance is accepted. Also, such components might have to be replaced over the wind tunnel's life cycle. But the Wind Tunnel Control System (WTCS) is software, and software does not age.

However, requirements evolve. New test scenarios come up. In compliance with regulatory guidelines requirements for documentation or traceability will change and become more challenging to keep up with. IT- and information security guidelines are evolving. Aspects of energy efficiency, increasing time and cost efficiency add to that.

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These changing requirements impose increasing requirements on the WTCS, which likely was well-suited to orchestrate the subsystems of the original wind tunnel setup. For some time, adding new functionality by attaching another tool, another script to the existing WTCS might work. But at some point, the requirements have changed dramatically. Thus, an outdated, pure SCADA system cannot keep up with the modern world of aerodynamic, aero-acoustic or thermal testing.

Then, it is time for a change. A modern, flexible, and adaptable IT-system, suited for control of all subsystems, for thorough data handling, process-safe information tracking, and efficient test-process automation is a major upgrade. It can significantly boost the facility's performance in efficiency, data and process quality, as well as test capabilities. However, such upgrades are major interruption of operation and may cause a ripple effect of remodeling interfaces or replacing hardware in all subsystems.

Thus, such upgrades are often avoided as long as possible, adding more extra tools, scripts, workarounds, operational procedures to keep the old world intact. However, this means investing more into obsolete systems and infrastructures, further losing ground to competitors, and increasing the effort when eventually deciding to upgrade.

Thus, it is important for wind tunnel centers to find ways to upgrade their control systems in a convenient way. Similarly important for system suppliers is to develop WTCSs with configuration and comfort features, to enable such upgrades with minimal downtime at minimal cost for the wind tunnel center.

The following sections describe the relevant aspects of WTCSs, reasons to upgrade to a more modern solution, the state of the field in terms of upgrade procedures as well as the common pitfalls. Then a novel approach is developed, the necessary improvements to WTCSs for such approach are described, and the benefits of this concept are highlighted.

2 Wind Tunnel Control Systems

The main task of a WTCS is interaction with the wind tunnel's subsystems. It sends setpoint commands controlling the test conditions. It reads status information and measurements and orchestrates the operation of all subsystems. Communication relies on industrial communication protocols like ProfiNET; OPC UA, etc., but also, proprietary Ethernet-based communication. Some subsystems are even controlled by analog and digital I/Os. Each subsystem exhibits a certain interface behavior, i.e. a certain way to react to commands, faults, etc. A well-defined architecture would standardize this behavior for all subsystems allowing easy modifications. However, each WTCS has different behavioral preferences. Thus, replacing the WTCS results in interface adaptation either within the new WTCS or in each connected subsystem.

Data obtained from subsystems is distributed to other subsystems for coupling and interlocking. Data is also presented in the user interface. Thus, data distribution is an important task. Often, hard links have been established, e.g. by (physically) wiring signals between subsystems. This might work while the architecture is constant, but it poses challenges when replacing subsystems. Thus, routing all data through the WTCS is advisable. Its subsystem interfaces act as hardware abstraction layer and ensure that changes to one subsystem don't affect the others. Also acting as "behavior abstraction layer" the interface drivers can provide a high degree of agnostics for each subsystem towards the WTCS and other subsystems.

All data shall be recorded. Continuous data recording in a ring-buffer database enables maintenance and fault-finding. Test-related, file-based recording in text or binary formats ensures all information about a test is stored in a dedicated place. Use of standard formats is advisable for easy access by all stakeholders. The formats should allow structured metainformation storage from test definition and documentation alongside the time-series data. Such metainformation is important for traceability and test documentation. Storage in text-files with minimal header information is no longer suitable. Instead, formats with extensible, indexed metadata are advantageous.

Recorded and live data commonly require processing. Derived quantities are calculated online from raw data, e.g. the wind speed from pressure differences in the plenum or nozzle. Statistics are calculated on recorded time series, data is checked for limit violations, etc. Thus, a configurable online calculation module computing derived quantities based on formulas is needed. Those math operations shall be adaptable to new situations, e.g. re-calibration, new entities, changes in parameters sets, etc. A suitable automated post-test analysis system should be included. To meet changing requirements, the analyses executed on test steps, test runs, or the test session must allow flexible modifications on processing and reporting.

The data obtained is visualized in standardized tables, graphs as well as specifically designed schematics of e.g. the cooling system, safety-related signals, etc. Also, historic data for trends as well as meta-information of the test are important to display.

Besides visual inspection of the data, automated monitoring is important. Failures or unexpected events should stop the test sequences. Notifications about violated test conditions help save time, otherwise wasted on unusable results. Further monitoring might be useful for process automation. The concept of monitoring parameterized rules, and on occurrence reacting with a certain sequence of steps is quite universal.

As results are only meaningful in context of the test description, thorough test management, describing the test is important. Also, integration with the department's test process is necessary. For uninterrupted operation, even without connection to central test planning, a local test management with reasonable capabilities including change tracking in compliance with ISO17025 [ISO17a] should be part of a WTCS.

Documentation of the tests starts with automated generation of reports without manual interaction to ensure no tampering with data can occur. But there are other aspects: photo documentation of the vehicle during a test run proves that test description and actual execution configuration match. Logging user comments and notes is also part of the ISO17025-compliant documentation.

All shall be in the context of the test description and results for a comprehensive and conclusive data set. Thus, data management is important. This includes archiving data to central test result management systems, removal of outdated data after archiving as well as separation of data belonging to different customers of the facility.

Automated test sequencing allows efficient test execution. Such sequences shall be easy to generate (e.g. from setpoint lists) and shall simultaneously be curated and quality assured for reproducibility and traceability by using templates. They should allow for a maximum of automation for a maximum of efficiency in test execution.

Collaboration between the operator and the test engineer is key for efficient and successful operation. Thus, both should have access to all relevant information. This includes viewing data, but is most powerful, when enabling the engineer to enter data defining upcoming test runs while the operator focuses on the execution.

Also, system administration is important. While overseeing daily operations, the wind tunnel engineer is responsible for first level support and maintenance. With an aerodynamics background, this person usually does not have in-depth IT knowledge. Thus, the administration, fault finding, etc. must be suitable for a trained user instead of a team of IT experts. In addition, recurring tasks should be encapsulated and automated to minimize the time effort required for routine maintenance.

The wind tunnel department is interested in process data and KPIs of the facility. While long-term storage and analysis of such data is not the primary scope, the systems should support necessary recording and processing to provide such data in a suitable way to department systems for further investigation.

3 Reasons for an Upgrade

There are various reasons to upgrade a WTCS. Most common is a major renovation of subsystems. Then, WTCSs with hard-wired or hard-coded interfaces require a significant redesign. Thus, it is a common time to decide on a completely new WTCS.

Also, the lack of test management or documentation in older systems leads to such decisions, especially with new norms and regulations. With stricter homologation requirements (e.g. in the context of WLTP [WLT21a]) thorough documentation of test conditions and results becomes mandatory [Jac24a]. ISO17025-compliant test processes require integration into department-wide test workflows, change tracking and data integrity measures. These are not easily achievable with legacy systems. Thus, upgrading to modern systems with integrated test management, photo documentation, change tracking, and quality assured data handling is advisable.

Lack of modularity and extensibility can lead to a deadlock where new features (e.g. support for active aerodynamic components [Jac25a]) cannot be added – or at extreme cost. Thus, the desire to enhance efficiency, capabilities or quality by new features can be another important reason for a new WTCS is necessary.

Old systems might not be compatible with new operating systems. Porting the existing system can be expensive if the software is not based on a platform with longevity in mind. Also, IT- and data security are increasingly important. Shared logins must be replaced with personalized accounts.IT infrastructure must enforce password rules and changes. Data security calls for separation of data of various customers, protection of personal data, etc. Achieving this requires significant reorganization and reprogramming for legacy systems. Such aspects can also lead to renewal.

4 Usual Upgrade Procedure

The usual upgrade procedure of a WTCS as outline in Figure 1 starts with gathering information about the interfaces of the subsystems. As the subsystems should be kept constant to avoid complexity and cost, full understanding of the data, the exchange mechanism as well as the subsystems' behavior is required. This involves extensive forensic work as old interfaces are often not well documented. Anything missed here has a significant impact on the commissioning of the new WTCS with unpleasant surprises later. Next, the features and capabilities of the new WTCS are specified.

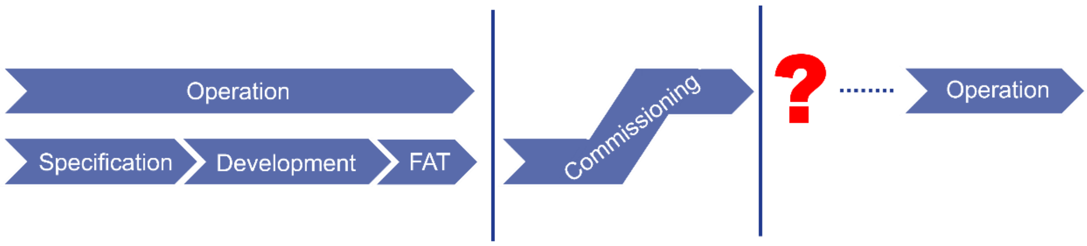

Figure 1: Common workflow of traditional wind tunnel control system upgrades

On this basis, the WTCS is implemented. If changes to subsystems are planned, this happens in parallel. After completion of software development, the operation of the facility is halted. Now there is no way back to the old system. The old WTCS is removed, physical interfaces are modified, and installation of new hardware begins.

Commissioning begins with subsystem interface tests. For a new wind tunnel, the subsystem supplier joins these tests. However, when upgrading, the subsystem supplier is usually not involved as their system was delivered long ago. They might even be no longer in business. The software supplier must test the interfaces alone, without support. Findings must be analyzed without insights into processes within the subsystems, and all solutions must be found within the new WTCS. There is a high risk of blocking issues, unexpected delays, and added cost for spontaneous changes.

The commissioning phase continues with complete tests of the new WTCS, the site acceptance test, and training for the operating and administering personnel. Finally, operations can be ramped up again. In the first weeks and months, the personnel will still have to acquaint themselves with the new system, its workflows and features. Thus, fully efficient operation will commence only after a certain time.

5 Downsides of a traditional Upgrade

The major downside of such an upgrade is the risk in identifying the exact behavior of the subsystem interfaces by complicated forensics. Any mistakes or missed information can result in massive issues later. It requires a traditional, lengthy specification as the supplier of the new WTCS must be familiarized with the wind tunnel center's detailed needs and wishes. The supplier needs a stable specification to have confidence in the tasks and work packages. However, the wind tunnel center might not have the time and resources for a full specification phase.

If old subsystem interfaces cannot be fully specified from available information or forensics, it might be necessary to involve many suppliers, and some might not be in business anymore. Thus, this can become a very complex project. The uncertainty in subsystem interfaces also bears a high risk of additional cost and delays, up to the point that the facility might not be operational due to blocking issues.

Shutting down operation on a certain date, then installing the new WTCS over several weeks, with the risk of delays in case of unexpected roadblocks, results in a long, unpredictable downtime of the facility. This queues up tests of important vehicle development projects, and results in significant revenue loss.

The steep learning curve when the new system becomes operational can lead to beginners' mistakes and decreased productivity in the first month of operations. This can be a prolonged period of unreliable, inefficient operation.

6 A novel Approach

Thus, a different approach as outline in Figure 2 is necessary. Instead of project-specific development, it requires a configurable, adaptable and easily integrated WTCS. Yet, the system must allow project-specific modules resolving roadblocks, which pure configuration cannot resolve.

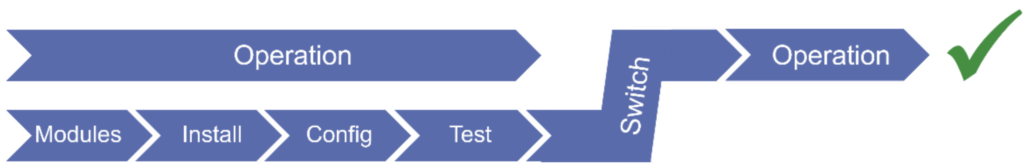

Figure 2: Workflow of novel wind tunnel control system upgrades

Ideally, the software is easy to install like office software. Thus, a downloadable installer, provided by the WTCS-supplier is the starting point. It can be installed and configured by IT-affine wind tunnel personnel on common hardware, and should contain necessary secondary installers to set up the WTCS on operator and customer workstations, etc.

Integral part of the concept is configuring the new WTCS in parallel while still using the old software. After basic installation, the subsystem interfaces can be configured one by one. Unused times (e.g. night shifts) can be used for communication tests with subsystems. Some communication settings of computers and subsystems might require changes to switch between systems. But, in general this allows further operation of the old WTCS without influence by and on the modernization project if the subsystem interfaces do not rely on hardwired signals. The new WTCS provider can support this with workshops and trainings, during which first configuration steps are taken together. Then the wind tunnel center can continue with further subsystems or additional settings saving cost of external personnel.

An important aspect is the ability to import and export the configuration in parts and in full. This allows frequent backups to keep the last viable state and is helpful for exchanging information between the WTCS supplier and the wind tunnel.

With such an approach, the facility can be operated with the old software until the very end. Then the new, fully configured and tested system is activated for a seamless transition. Defining test suites to validate the expected behavior and results and executing them with the old and the new system gives confidence in operational robustness and validity of results. As personnel is already working with the new solution for a while during the configuration and testing, the transition process is much smoother, and a higher operational efficiency from day one can be achieved.

7 Necessary Improvements of Wind Tunnel Control Systems

The provision of a configurable platform as shown in Figure 3 instead of project-specific solutions is a major paradigm-change. The approach is not new, but often not applied to niche-software like WTCSs. Such does not favor implementations of expensive configurable modules over static, but cheaper hard-coded one-off solutions. Thus, the approach is only suitable when having a significant client base with multiple installations.

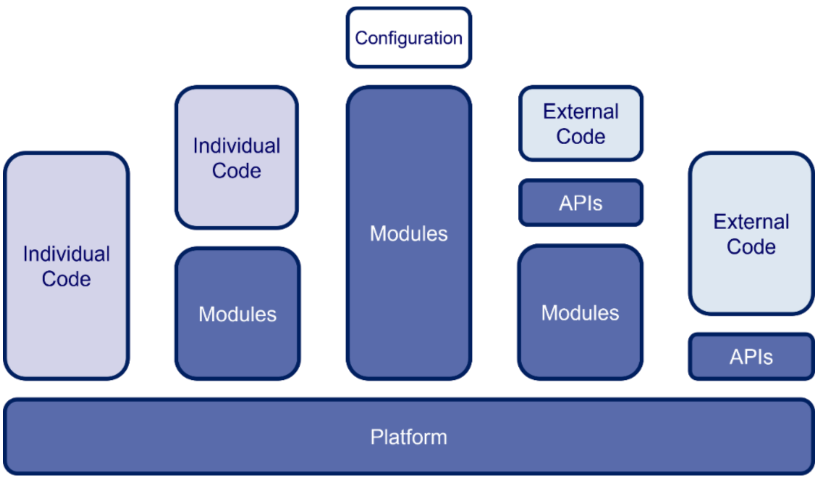

Figure 3: Platform concept

Meeting the specific requirements for a certain wind tunnel requires a modular approach. Distinct components should be separate platform modules, only included in a system, if required. This allows lean solutions to support a broad range of scenarios.

Tailoring the WTCS to a specific wind tunnel in a no-code approach requires convenient, end-user suitable configuration editors. These shall guide a domain expert with minimal system knowledge in configuring subsystem interfaces, control displays, data distribution, processing, and recording. Instead of technical aspects, logical domain components shall be the configured building blocks.

For aspects, requiring more than just configuration, where a no-code approach is not sufficient, a low-code approach should be followed. Scripting capabilities can tailor the behavior of the system, e.g. by integration of analysis scripts for tools like DIAdem, Excel or Matlab to process the result data automatically.

The concept is not limited to data analysis. It can be extended to most specific tasks going beyond configuration by utilizing scripting languages like Python. This can also include suitable APIs allowing development of specific code modules as outlined in Figure 4 or SDKs and plugins as exemplarily shown in Figure 5 for a subsystem interface driver. By providing such in various languages, including scripting languages, users can easily extend and customize the system to their specific needs. In addition, integration with external tools, which might provide valuable functionality already at hand in the department, can significantly improve the benefits of such solution.

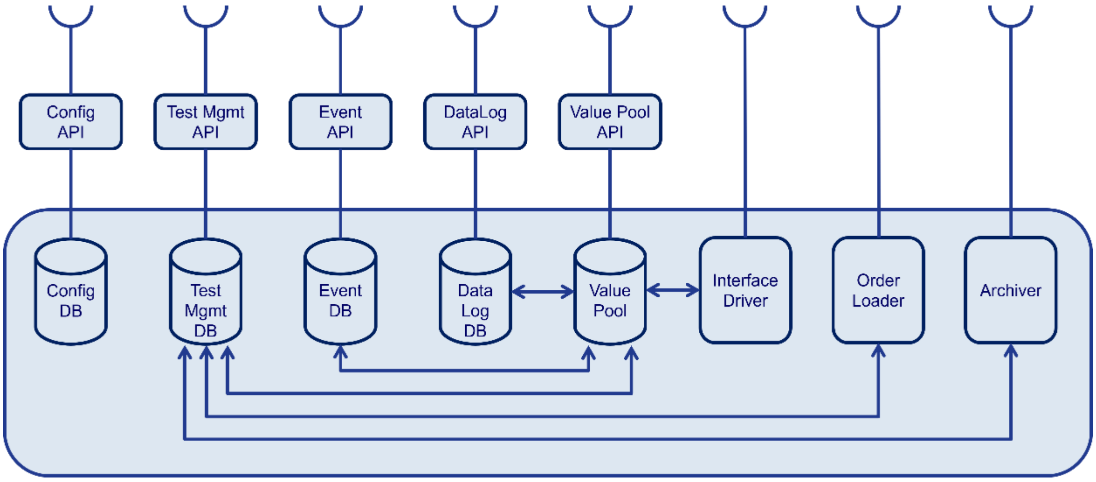

Figure 4: APIs and Interfaces

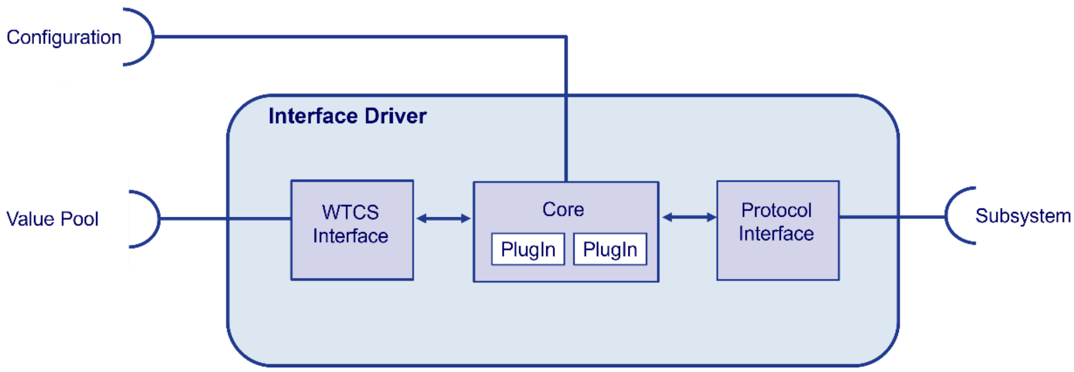

Figure 5: Architecture of interface drivers with modular interfaces and plugins

To keep track of the system configuration and allow for continuous support of such a modular solution with a lot of configuration options by the wind tunnel center, the software must allow for easy and reliable backups of the whole configuration as well as for distinct parts of that. Such saved configurations must be easily exchangeable between the supplier and the wind tunnel center to ensure both ends always have the same configuration at hand in case of updates, fault-finding support and consulting for modifications. Thus, thorough configuration management and tracking must be established as well as a reliable mechanism providing the wind tunnel with easy to install updates, setting up new software versions including the required configuration and without voiding the already made configuration settings on site. Such is also of importance in the context of IT- and information security standards like ISO27001 as well as for the traceability and reproducibility of tests as the software configuration is also part of the test setup. Figure 6 schematically shows such process for platform code, project configuration management, update generation, execution, and configuration feedback.

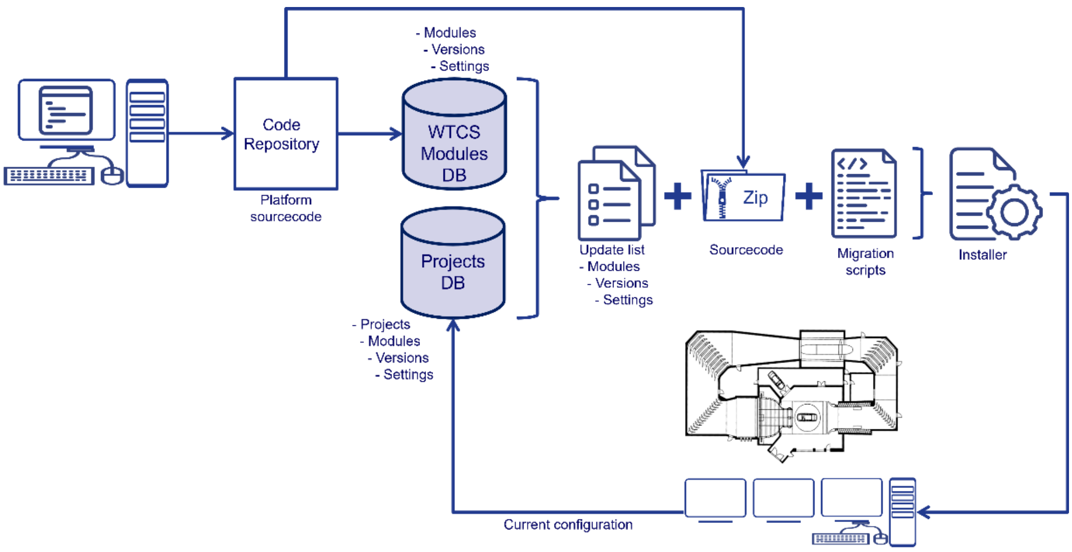

Figure 6: Concept of a version and configuration management cycle

In support of the wind tunnel personnel, the WTCS provider must have suitable domain-experts in operative and supervisory control aspects of aerodynamic and climatic wind tunnels, who at the same time have strong IT knowledge. For designing the system and for execution of successful workshops transferring knowledge from the provider to the owner such highly skilled and knowledgeable experts are of key importance to project success.

8 Benefits of the Approach

Such an approach offers benefits with respect to time, cost, and operations. By purchasing licenses of proven software, while installing and configuring it mostly on their own, wind tunnel centers can significantly reduce costs. Estimates from the first projects show a reduction by up to 50% of external cost.

The approach also offers a lower risk as the parallel operation allows most settings to be tested prior to the final system switch. The point of no return is only reached when new or changed subsystems are only integrated into the new system.

Simultaneously, this reduces downtime of the facility as full operation is possible for most of the time. Thus, the wind tunnel can still be operated, and be profitable, while the new system is commissioned in the background.

Using a platform ensures higher robustness than individualized coding while ensuring maximum functionality as it bundles features from the experience of many customers.

Tailoring the functionality by choosing the right modules and configuring them as needed gives a perfect fit. Each wind tunnel receives exactly the features it requires. Customization is easily done on-site by the wind tunnel center as many aspects are configurable for the user. APIs allow realizing own ideas independently. At the same time, a reliable partner also allows for such modifications done externally.

Always being operational, without deadlines or deadlocks, makes a painless transition possible. The upgrade is efficient. Administrators and operators learn to use the new software while configuring the system, giving them a head start with the new WTCS.

Such a WTCS is a perfect match by seamless integrating into various IT environments and test process workflows. Together with the modularity and configurability of the WTCS allows to easily interact with test resource planning, test definition, and results management systems for seamless, robust and certifiable processes.

9 Benefits beyond Upgrade Projects

The same advantageous features for such an upgrade project also provide benefits in other situations like setting up the WTCS for a new wind tunnel or during operation, when adapting to new requirements and new functionalities.

A strong user community and a supplier actively investing in the future of the platform ensures constant development to stay ahead of the curve as wind tunnel center. The easy expandability of a modular platform in combination with a domain-expert software supplier ensures wind tunnel centers can fulfil their constantly evolving ideas with such a solution in minimal time at reasonable cost. The common platform with a broad installation base allows to benefit from innovative new modules, which were developed by the supplier in response to market requests as such modules can be added to installations of all customers.

9.1 New Wind Tunnels

All benefits of a configurable solution apply here, too. Yet slightly more specification work and interface testing is needed as coordination with the subsystem suppliers is required, compared to a refurbishment project, where the interfaces are usually as is.

If the configuration dialogs allow for export of the configuration in a readable way, it is possible to minimize the additional workload by directly configuring the system and extracting the configuration as specification instead of first generating paper documents and then typing the same information into the configuration.

9.2 During operation

The modularity of a platform ensures easy integration of add-ons and new modules. A high degree of configurability ensures quick changes without significant cost or time needed. The widespread use of a platform always ensures reliable operation of the system, during normal operations as well as during upgrades. Even in case of failure, a platform-based solution has the advantage of well-established error handling and bug reporting allowing for easier recovery and faster fixing of issues.

10 Conclusion

Complex IT systems like a WTCS can be easy to install and configure, allowing cost-effective and hassle-free upgrades of existing facilities Individually hard-coded software development is replaced by a modular and configurable platform. In line with a no-code/low-code concept functionality and behavior are defined by configuration and scripting. Plug-in architectures and APIs seamlessly bridge any gaps in the few situations still requiring coding. This provides modern features for test management, documentation, and efficient operation to older facilities. Further, it ensures constant improvements over the life cycle minimizing the risk of another upgrade drastically. The self-paced and training-supported upgrade path ensures familiarization of the operating and administrating personnel for a smooth transition to a future-proof control system supporting the needs of modern wind tunnel facilities.

11 Reference list

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