PROPHESY

Platform for rapid deployment of self-configuring and optimized predictive maintenance services

DELIVERABLE

# D6.1 – Service Bricks Specifications v1

Horizon 2020 European Union funding for Research & Innovation

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# Executive Summary

This report specifies the PROPHESY "constituent components" that comprise the building blocks of an integrated PdM service or solution. The definitions of "Service Bricks", "Connectors", "Tools", "Services" (as well as their subtypes) are presented in detail. A comprehensive taxonomy of the above entities is provided in terms of type, use, provider, category, instance and other important properties. Deployment and Packaging rules for them are also initially addressed, although these will be further refined thoroughly during technical and development work packages WP3, WP4 and WP5.

Most importantly, a methodology for the combination of "Service Bricks" and other building blocks into "Solutions" is introduced as input for the ensuing Task 6.2 for the PROPHESY-SOE, since the ultimate end-product of the entire WP6 is the composition of "optimized turn-key solutions in Predictive Maintenance", in order to target specific KPIs at first, and to subsequently offer cost-benefit calculations of the deployment. Attention is also given to augmented complementary services in the form of consulting, training, technical support, what-if-analysis and ultimately all support services offered expected during solution composition.

In that scope, the report makes sure to provide a "business viewpoint" above the plain technical specification layer, to indicate how PROPHESY will not only validate its results within the two complex demonstrators real manufacturing plants; but will also be in the position to deliver similar solutions for any other future prospective beneficiary through its ecosystem. In a sense, one could view the demonstrator cases as specific "instances" of a more generic turn-key solution composition mechanism.

Finally, incorporation and presentation within the PROPHESY ecosystem platform is addressed, as an aggregation point with a twofold purpose: Community building and Service Offering.

This deliverable as part of Task 6.1 "PdM Service Bricks Specifications and Adaptation" offers the output that constitutes the first step in the chain of WP6 activities i.e. identifying and packaging data-related service bricks (including models, data collection and analytic components). These are the cornerstone upon which the next WP6 objectives will build on.

This document is the first version of the Service Bricks specification, since a second (and final) version is expected to be delivered in M24 entitled "Service Bricks Specifications v2" once technical fine points will be elaborated.

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# Definitions, Acronyms and Abbreviations

| Acronym/ Abbreviation | Title |
|---|---|
| **API** | Application Programming Interface |
| **AR** | Augmented Reality |
| **B2MML** | Business To Machine Mark-up Language |
| **CAE** | Computer-Assisted Engineering |
| **CBM** | Condition Based Monitoring |
| **CMMN** | Case Management Model and Notation |
| **COTS** | Commercial Off-The-Shelf |
| **CPPS** | Cyber-Physical Production System |
| **CPS** | Cyber-Physical System |
| **CPSoS** | Cyber-Physical System of Systems |
| **CRISP-DM** | Cross-Industry Standard Process for Data Mining |
| **CTQ** | Critical To Quality |
| **DCS** | Distributed Control System |
| **DPWS** | Device Profile for Web Services |
| **DSS** | Decision Support System |
| **DA** | Data Analytics |
| **DC** | Data Collection |
| **DV** | Data Visualization |
| **EOL** | End Of Life |
| **ERP** | Enterprise Resource Planning |
| **FIPA** | Foundation for Intelligent Physical Agents |
| **GUI** | Graphical User Interface |
| **HFML** | High Frequency Machine Learning |
| **HMI** | Human Machine Interface |
| **IACS** | Industrial Automation and Control Systems |
| **ICS** | Industrial Control System |
| **IEC** | International Electrotechnical Commission |
| **IIC** | Industrial Internet Consortium |
| **IIRA** | Industrial Internet Reference Architecture |
| **IIoT** | Industrial Internet-of-Things |
| **IoT** | Internet-of-Things |
| **IPR** | Intellectual Property Right |
| **ISA** | International Society of Automation |
| **IT** | Information Technology |
| **KPI** | Key Performance Indicator |
| **LFML** | Low Frequency Machine Learning |
| **Local DSS** | It is a DSS local to the PRPOPHESY-CPS |
| **M2M** | Machine to Machine |
| **MGMT** | Management (short for service brick cross function) |
| **ML** | Machine Learning |
| **NIST** | National Institute of Standards and Technology |
| **OEE** | Overall Equipment Effectiveness |
| **OEM** | Original Equipment Manufacturer |
| **OPC** | OLE for Process Control |
| **OPC-UA** | OPC Unified Architecture |

| | |
|---|---|
| **OT** | Operation Technology |
| **P&P** | Plug and Produce |
| **PdM** | Predictive Maintenance |
| **PLC** | Programmable Logic Controller |
| **PLM** | Product Lifecycle Management |
| **PROPHESY-AR** | PROPHESY-Augmented Reality |
| **PROPHESY-CPS** | PROPHESY-Cyber Physical System |
| **PROPHESY-ML** | PROPHESY-Machine Learning |
| **PROPHESY-PdM** | PROPHESY-Predictive Maintenance |
| **PROPHESY-PdM Platform** | The hardware and necessary software connected to several PROPHESY-CPSs and to the PROPHESY-AR. The platform is responsible to calculate KPIs from the data and using the PROPHESY-ML algorithms. |
| **PROPHESY System** | It is the combination of the PROPHESY-CPS and PROPHESY-PdM platform |
| **PROPHESY-SOE** | PROPHESY-Service Optimization Engine |
| **QMS** | Quality Management System |
| **RAModel** | Reference Architectural Model |
| **RAV** | Replacement Asset Value |
| **RCA** | Root Cause Analysis |
| **REST** | Representational State Transfer |
| **ROI** | Return On Investment |
| **RTD** | Research and Technology Development |
| **RUL** | Remaining Useful Life |
| **SB** | Service Brick |
| **SEC** | Security |
| **SOA** | Service Oriented Architecture |
| **SOE** | Service Optimization Engine |
| **SoS** | System-of-Systems |
| **SotA** | State-of-the-Art |
| **SSN** | Semantic Sensor Network |
| **STDP** | Security, Trustworthiness and Data Protection |
| **TCM** | Total Cost of Maintenance |
| **TRL** | Technology Readiness Level |
| **UC** | Use Case |
| **UX/UI** | User Experience /User Interface Design |
| **WP** | Work Package |
| **WS** | Web Service |

# 1 Introduction

## 1.1 Methodology

In brief the deliverable aims to achieve:

- Formalization of definitions and of constituent components
- Identification and categorization of building blocks and service bricks, deployment/packaging introduction, and isolation of application-specific connectors
- Introduction of Stand-alone solutions, Business Services and their elements
- Mapping the business logic the "Target-KPI-Cost/Benefit-Decision" chain of actions
- Insights on designing and developing a service brick oriented ecosystem platform

In the end, the reader must be able to distinguish among the entities: service bricks, tools, connectors and services. Also to be able to decipher how the KPI chain works business wise, what the tools aim to achieve as a process, and how exactly each solution is to be aggregated from constituent components, always assuming a "business view point" irrespective of technicalities.

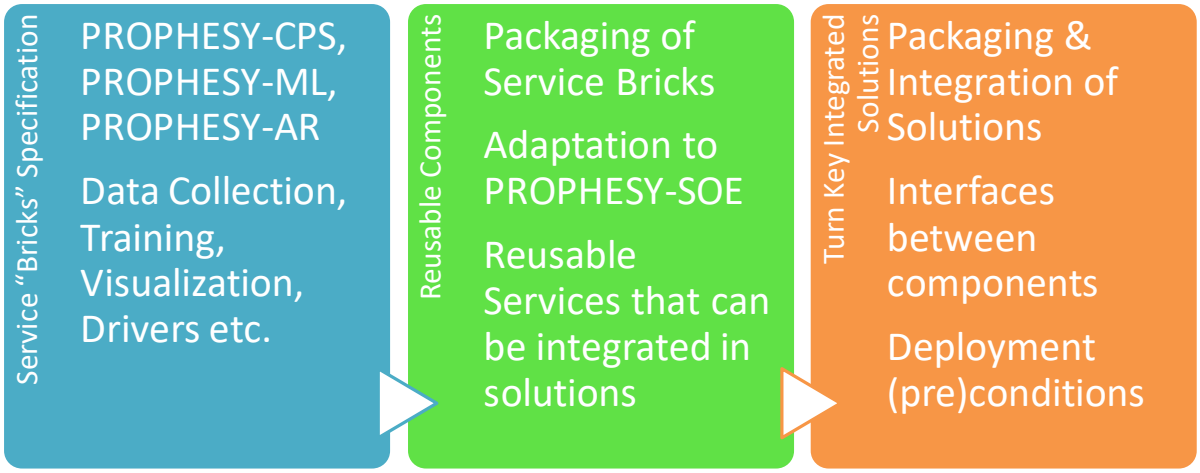


*Figure 1: The PROPHESY Approach to Turn Key Solutions Composition and Deployment*

## 1.2 Relationship to other deliverables

This Document's initial input has been the first candidate list of components as circulated during D2.3 development, providing the initial specification of the "service bricks" and the SOE. It has also taken into account D2.4 concerning the Demonstrator use case instances and complements D2.5 about the PROPHESY ecosystem, defining its business viewpoint, service offering and added value when integrated with the constituent components.

By refining the list of constituent components, and through its building block definitions, this deliverable also provides the basic input for D8.2, linked to KPIs that will be used to evaluate service bricks and turn-key solutions as well as D8.7 relating to the exploitable assets of the

project during sustainability stages. It also provides insights on business roles of partners, also relevant for D8.7

Most importantly though, this deliverable as output of Task 6.1 "PdM Services Bricks Specifications and Adaptation" offers the cornerstone building blocks that constitute the first step in the chain of WP6 activities. It forms the basis upon which the next WP6 objectives will build on. Namely:

- To implement techniques for composing services and integrating turn-key solutions. (Task 6.2)
- To design and implement data-driven techniques for calculating KPIs associated with assets and asset management, fully in line with the ISO 55000 standard (Task 6.3).
- To explore and implement business models concerning the real-life deployment of turn-key solutions based on the PROPHESY-SOE platform (Task 6.4).
- To provide tools for cost-benefit calculation of turn-key solutions (Task 6.5).

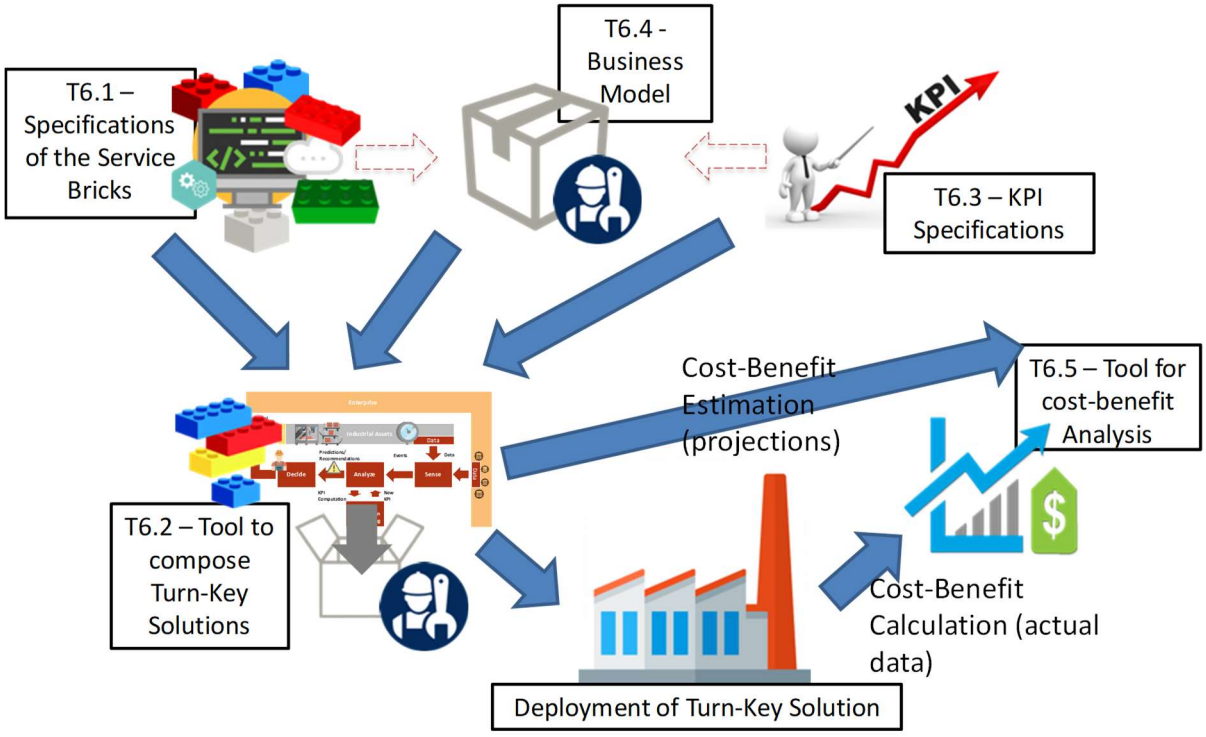


*Figure 2: WP6 Task dependency in the business chain of solutions creation*

Hence, D6.1 also illustrates the connecting business logic and methodological overview of the KPIs, the KPI calculator, the Cost Benefit Analysis, the Solution composition, and offers the business chain insight of how these next deliverables will be developed into a seamless structure to offer services through the PROPHESY ecosystem.

## 1.3 Document Structure

The current document is structured as follows:

- Section 2, following this introductory section, characterizes the building blocks of PROPHESY, provides their strict definitions and illuminates how their aggregation into higher-level entities will work.
- Section 3 illustrates every single Service Brick, outlines their layers and categories, particularizes on connectors, and then proceeds by defining the PROPHESY Tools and exemplifying the connection of KPI and Cost-Benefit Functions in detail.
- Section 4 introduces concepts for packaging and deployment of Service Bricks.
- Section 5 is devoted to Solution Composition Methodology, Metric and KPI identification, but most importantly illustrates the business viewpoint of PROPHESY.
- Section 6 demonstrates stand-alone application services and the augmented business services of PROPHESY.
- Section 7 provides insights on the coherent presentation of the PROPHESY constituent components within its Ecosystem, the services envisioned to be provided to 3rd parties and the demand/supply side stakeholders that will form its contributing community.
- Section 8 is the final and concluding section of the deliverable.

Appendices illustrate the analytical tables of: core service bricks, connectors and Universal PdM KPI candidate list.

# 2 PROPHESY Building Block Taxonomy

## 2.1 Definitions

The following definitions are universally used throughout the PROPHESY project and apply to the entire chain of "solution creation" for any use-case (UC) and are uniformly used among deliverables.

PROPHESY uses uniformly the following terms for its architecture:

| | |
|---|---|
| **PROPHESY-AR** | PROPHESY-Augmented Reality |
| **PROPHESY-CPS** | PROPHESY-Cyber Physical System |
| **PROPHESY-ML** | PROPHESY-Machine Learning |
| **PROPHESY-DV** | PROPHESY-Data Visualisation |
| **PROPHESY-DC** | PROPHESY-Data Collection |
| **PROPHESY-SOE** | PROPHESY-Service Optimization Engine |
| **PROPHESY-PdM** | PROPHESY-Predictive Maintenance |
| **PROPHESY-PdM Platform** | The necessary hardware and software connected to several PROPHESY-CPSs The platform is responsible to calculate KPIs from the data acquired through PROPHESY-DC, using the PROPHESY-ML algorithms, present them through PROPHESY-DV and lead to meaningful business decisions |
| **PROPHESY System** | The aggregation of the PROPHESY-CPS and PROPHESY-PdM platform combined with consulting services of partner experts |

*Table 1: PROPHESY Basic Architecture Terms*

A clear distinction must be made in the terminology concerning what constitutes a **solution** for an end-user or beneficiary (JLR, PHILIPS, MAG being the UC demonstrators) versus the more general case of any future potentially interested 3rd party that visits the PROPHESY ecosystem in search for a PdM "integrated solution". The former type of solution is UC specific (more of an "instance" as described below), whereas the latter takes advantage of the ubiquitous architectural structure of "**service bricks**", "**building blocks**" and "**tools**" -as described below- to address much broader needs for a much wider PdM application's audience.

The notion of a "solution" in principle can either be an "integrated" turn-key solution, or sometimes it can only be an optimized subset of the following terms which can still be stand-alone solutions themselves.

**DEFINITION**: The terms below are the **building blocks** that PROPHESY PdM Platform uses:

## 2.2 Service Brick

Sets of components developed and combined together throughout PROPHESY, in order to formulate "distinct" pieces of PdM specific software modules (in general) but which may also include hardware, sensors, and related data collection modalities. They are in principle re-

usable and can be combined together in a unified manner through the PROPHESY-SOE. It will be shown that some are application specific and hence might require slight adaptation for possible re-use.

Service Bricks have a specific "purpose" and a common framework for "inputs and outputs". Their inherent objective as the name suggests is to provide a "service" or to be combined into a "service". All service bricks (probably including connectors if IPR permits so, see D8.7 for details on IPR) will be available within the PROPHESY ecosystem (See D2.5 for the ecosystem initial specification) for independent stand-alone use, combination into higher level entities (which is their primary purpose), as well as for evaluation from prospective future beneficiaries beyond JLR, PHILIPS and MAG during exploitation and sustainability stages.

## 2.3 Connectors

An exceptional type of Service Brick, specifically designed for communication with specialized equipment within a Predictive Maintenance use-case. One could consider those an "instance" of a Data Collection modality, due to the requirements of a particular UC. Unlike all other service bricks, this is a type that cannot be re-used in a different business context without slight modifications and might also be bound by licensing for internal use only. Connectors are not exactly "service bricks" per se, but their presence is dictated by the need to combine other service bricks within a use-case. Connectors have a higher "granularity" when breaking down the platform into components. As properly and simply put by PHI and JLR partners who have the hands on expertise on the Use cases at hand, one could define connectors as entities implemented "to feed information back into an existing database or dash-boarding platform of the end customer".

## 2.4 Tools

Integrated complementary software (or even combinations of software and hardware such as an integrated Data Collection product) which have the distinctive feature of **not** being composed by service bricks of PROPHESY, but being built by partners, during and for the PROPHESY project, in parallel with service bricks during the development stages. They are innovative in the sense that they will be built "from scratch" specifically for use with the PROPHESY Solution creation methodology and are essential building blocks in the formulation of a complete turnkey solution to an end-user in parallel with service bricks. Tools are a crucial deliverable available within the PROPHESY Ecosystem and can be used either autonomously or in combination with service bricks and offer integrated services. Tools include:

- the KPI Calculator,
- The Cost-Benefit Calculator,
- The Service Optimization Engine (SOE)
- Any other turnkey composition tool (as introduced in D2.3) as well as any other candidate complementary application to the service bricks that might need to be developed in the scope of creation of integrated services.

**Clarification**: Existing Data Collection systems (e.g. MMS or ICARE) are not considered in this taxonomy as 'Tools' despite being called so by their respective owners before the project. In PROPHESY terminology they actually consist "Background knowledge" brought in and "inherited" in PROPHESY, and hence are handled according to the knowledge register and IPR management scheme as per D8.7. The term "PROPHESY Tools" is strictly reserved for those integrated complementary software entities developed "within PROPHESY" to serve as the joining and aggregating modalities that implement the WP6 business cycle (i.e from SB, to SOE, to solution creation, to KPI tracking, to cost-benefit Analysis for the beneficiary, as described in figure 2 above).

## 2.5 Services

Services can fall into one of two very broad categories:

### 2.5.1 Application Service

A carefully selected composition of service bricks and tools (or in the extreme case a single standalone service brick or a standalone tool) constituting an integrated system that works together to perform a Predictive Maintenance operation, calculate a quantitative metric and lead to a business decision. Services are generally composed through the PROPHESY-SOE with the typical need for their integration through human consulting activities and augmented business services (see below)

### 2.5.2 Augmented Business Service:

Types of complementary activity offered by partners either individually or jointly, whose offering is imperative in collaboration with the above categories in order to formulate a complete turn-key solution towards an end-user. It is generally in the form of consulting such as but not restricted to: Technical support, Technical Consulting, Business Consulting, KPI and Cost benefit formulation, needs and requirements formulation, Training services (including Training material) etc. It must be stressed that the word imperative above indicates the obvious assumption that there can be no integration of software, service bricks, tools or similar PdM IT solutions, into a meaningful turn-key PdM solution, without the human intervention of an experienced "consultant" who will at least formulate requirements, provide technical consulting and some form of cost-benefit and KPI definition in collaboration with the beneficiary, just as in every other ICT integrator scenario. It is clear that Augmented Business Services bear significant added-value within each integration both within the Use cases (UC) and any other future PdM application.

## 2.6 Solution

This is a "higher level entity" and comprises of any set of

- Tools
- Standalone service bricks
- Grouped service bricks into a service
- Augmented Business Services

- Combination of the above

into an aggregated entity (up to the highest level of a "turn-key solution") that can provide to an end-user or beneficiary within the wider Predictive Maintenance schema, a desired result or a conclusion towards a business decision.

Solutions can be provided in a twofold manner: Primarily when consulting an end-user/ beneficiary with a "given situation" in which case the desirable metric/KPI to be reached may be predefined, but also in the form of evaluation through the PROPHESY ecosystem by prospective users whose needs are not strictly formulated yet, but they simply seek to appraise and assess novel PdM alternatives before they are even ready to formulate their PdM problem to be solved. Simply put, solutions can either "solve an existing problem" or "present ideas of solutions and services to 3rd parties who still try to define their problem" The PROPHESY ecosystem provides examples of use-cases as guides to prospective evaluators.

## 2.7 Use Case "Instances"

Based on the above formal definitions, as well as considering the wider scope of the PROPHESY-SOE, the best way to view the specific use cases (UC) at the demonstrator's premises -as these are precisely described in D2.4, (i.e. JLR/PHI UC1, UC2, UC3, UC4, UC5, UC6)- would be to consider those UCs as specific "**instances**" of a more generic "solution", where individual connectors are also dictated to be developed for equipment communication reasons, a subset of distinct KPIs have been selected out of the multitude of possible PdM KPIs that could be applicable according to the beneficiary's needs, specific instances of the "Tools" will be employed in these UCs, and a set of specialized, explicit consulting services will be performed by PROPHESY Partners to formulate the final solution.

## 2.8 Exploitable Asset

Any entity defined above, (either standalone or combined into all possible intermediary aggregations up to the level of a turn-key solution), as well as any side product of PROPHESY not excluding intellectual property, that can be deemed commercially exploitable in the future by one or more project partners, is re-usable with minor modifications and may bear licensing, IPR, or other ownership schemes due to background knowledge preceding PROPHESY or foreground work performed within PROPHESY.

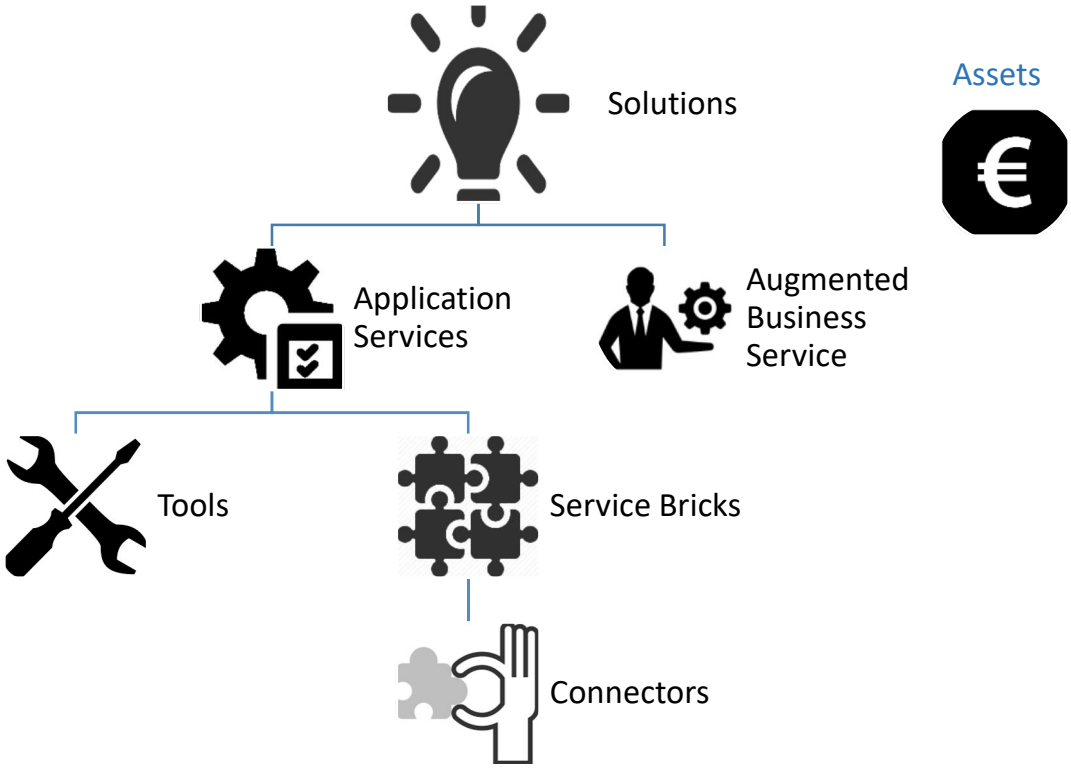


*Figure 3: Service Bricks and Building Block Hierarchy*

# 3 Building Block Specifications

## 3.1 Introduction to the Service Bricks List

An initial candidate list of "Service Bricks" was first composed using all partner feedback within D2.3 "PROPHESY-SOE". Moreover, the specifics of the use cases were also taken into account based on the "Complex Demonstrators Specifications" (D2.4) to further refine the list. It must be stressed that the JLR and PHI use-cases have a more particular focus on the specific "instance" of the demonstrator solution rather than a universal view of a broad case. In that sense there is not an exact 1 to 1 correspondence – and there should not be one in principle- between the "Service Bricks List" and the use cases "parts list" of D2.4 which drill down to much higher granularity by adding hardware and connectors "specific" to the use cases at hand.

As architecture and the prerequisite work packages have progressed (i.e. WP3 PROPHESY CPS Platform, WP4 PdM Data Collection and Analytics, WP5 PdM Visualization and Augmented Reality) the service brick list has been formulated to an updated form that is presented in (APPENDIX A) Tables A1 and A2.

An Analysis of SBs follows:

## 3.2 High-Level Classification of Service Bricks - "Functional Layers"

In accordance with the specifications of the most prominent standards such as Industry 4.0, the Reference Architectural Model for Industrie 4.0 (RAMI 4.0), Industrial Internet Reference Architecture (IIRA), the RAModel, and most other similar reference architectures, one could distinguish from a functional view-point 3 high level operational or "**functional layers**" into which service bricks can be grouped:

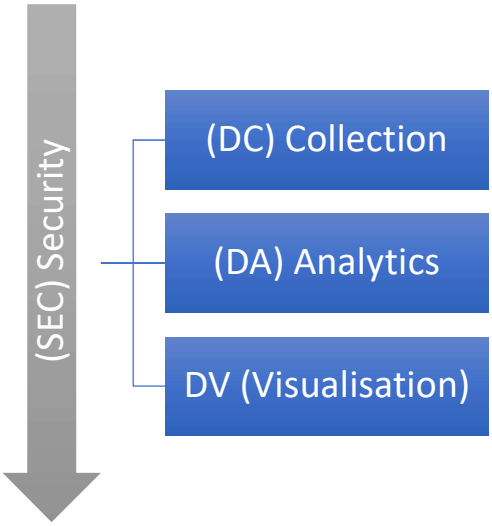


*Figure 4: Service Brick Functional Layers*

- Data Collection (DC)
- Data Analytics (DA)
- Data Visualization (DV)

This "categorization" (as DC-DA-DV) is perfectly in line with 3 key innovations expected to be produced by PROPHESY, i.e.

a. A CPS platform optimized for PdM activities (PROPHESY-CPS), which will enable maintenance driven real-time control, large scale distributed data collection and processing, as well as improved production processes driven by maintenance predictions and FMECA activities.
b. Novel Machine Learning and Statistical Data processing techniques for PdM (PROPHESY-ML), which will be able to identify invisible patterns associated with machine degradation and assets depreciation, while at the same time using them to optimize FMECA activities.
c. Visualization, knowledge sharing and augmented reality (AR) services (PROPHESY-AR), which will enable remotely supported maintenance that can optimize maintenance time and costs, while increasing the safety of maintenance tasks.

We can also decompose SBs into several Crosscutting (XC) Functions (vertical to layers) such as Management, Security, etc. In our case we have narrowed it down to only two cross-cutting function for reasons of simplicity, namely:

- Security (SEC) Service Brick
- Management (MGMT) Service Brick

## 3.3 Technical Classification "Categories"

Technical analysis performed in Task 2.3 and the first stages of WP4, has initially revealed that Service Bricks can belong to the following categories -a slightly more drilled down approach than layers- when seen from a technical viewpoint. Obviously, this is expected to be refined as WP3, WP4, WP5 progress, where many other aspects such as Input / Output of each service brick will be finalized.

1. **Security:** Meant to group all secure services. An example of use case is the anonymization or the encryption of the data.
2. **Middleware:** These provide data translation and convert between standards or communication formats. They should be used as an interface between systems with different I/O representation but the same information.
3. **Modelling:** Similar to middleware services these modules receive raw data and translate it to a known data type or structure. The main purpose of these services is to add context like metadata or to model data to a specific standard.
4. **Connector:** Grouping all the services which represent connectors to other modules or to another layer of the architecture. In principle they are a custom connection dictated by specific use case needs.
5. **Data analytics:** Explained in the next section
6. **Data Collection:** Explained in the next section
7. **Visualization & AR:** Explained in the next section

It should be noted that although Middleware, Modelling and Connectors might seem at first inter-related, performing "connection, translation and conversion", it was a specific partner

request during architecture discussions (WP3, WP4 and WP5) to keep them separated for specific technical implementation reasons, and not group them together as the operational view would suggest.

## 3.4 Security SBs

One central Service Brick has been identified in this crosscutting function, namely:

### 3.4.1 Security, Trustworthiness and Data Protection Framework

The STDP Framework led by MONDRAGON and FHG, is a robust framework that implements mechanisms to provide security the of PROPHESY-CPS platform at the network, device and cloud levels.

## 3.5 Management SBs

Two Services Bricks have been identified in this crosscutting function, namely:

### 3.5.1 Administration Shell

The Administration Shell is an official concept of the RAMI reference model [2] and is widely used in industrial IoT and Industry 4.0 architectures. This Service Brick, led by NOVAID, UNPARALLEL and SENSAP could further be decomposed (in higher granularity when refining into component level) into:

- Administration Shell  Manifest + Flows
- Administration Shell  API
- Administration Shell  Connectors

### 3.5.2 Self-Adaptation & Configuration Framework

The SACF service brick refers to adaptation management and is led by FHG. It deals with management and also decision support functions assisting in altering the adaptation strategy, and it belongs to the middleware category.

## 3.6 Data Analytics SBs

Machine Learning and Statistical Data processing techniques are integrated in the following Data Analytics Service Bricks:

### 3.6.1 The PROPHESY-ML Toolkit,

Led by AIT, MONDRAGON and TUE, it is a unified and reusable framework that integrates IoT data collection and selected data analytics schemes for Machine Learning, Data Mining and Statistical techniques for Adaptive Self-Configuring PdM programs.

It refers to implementation algorithms for Machine Learning selected, designed and/or customized for specific PdM purposes; in particular, the algorithms surveyed so far by partners focus on the UC instances, by estimating Remaining Useful Life (RUL), or at least useful bounds on RUL, which can then effectively be used to trigger Predictive or Condition-

based Maintenance actions. The algorithms surveyed will be published in a WP4 deliverable. They include so far:

- Artificial Neural Networks & Deep Learning Networks
- Bayesian Networks
- Support Vector Machines
- Decision Trees and Logistic Regression
- Boosting & Bagging Techniques
- Rule Learners (including RIPPER/SLIPPER/IREP, as well as Quantitative Association Rule Learning algorithms)
- Others including Clustering and Clustering-based regression methods etc.

### 3.6.2 QARMA Machine learning algorithms

Led by AIT, QARMA (short for QAR Mining Algorithm) is a new highly parallel algorithm suitable for running in elastic compute environments, for mining all interesting quantitative association rules, that is, non–dominated rules having support above a minimum support threshold Smin, and for a set of interestingness metrics (e.g. confidence) have levels above minimum specified threshold values Cmin. The scale-out capabilities of the algorithm make it particularly attractive because of the high compute intensive load it may require on large datasets.

The algorithm works on multi-dimensional datasets where items have many attributes (disjoint or not from other items' attributes) and produces all non-dominated rules that specify values for a single attribute of a single consequent item. The rules also specify minimum values for each specific attribute of each item in the antecedents of the rule. QARMA is significantly different from other algorithms as it does not use any value discretization or bucketing technique, and in addition guarantees the generation of all such rules.

The QARMA framework is ideally suited for a PdM task predicting upper-bounds in the RUL because it can automatically discover all non-dominated rules that indicate that a set of (rarely occurring) pre-conditions triggers a maintenance need. By specifying sufficiently low support levels so as to capture the rarity of the events occurring frequency, and at the same time specifying sufficiently high required confidence and lift or conviction values for the derived rules, the algorithm can produce a (possibly large) set of rules that trigger rarely, but when they do, they indicate with high likelihood the need for maintenance. Once produced, such rules are continually and automatically tested to see if they fire as new observations arrive. When they fire, they signal an alert for a maintenance need.

### 3.6.3 Data Mining Techniques

Led by MONDRAGON, this SB provides distributed machine learning techniques with focus on PdM to accurately derive maintenance predictions.

### 3.6.4 Data Analysis & Fine-Tuning (Modelling)

Led by TUE, takes mathematic models as input and provides Statistical algorithms based on dynamic decision thresholds for the maintenance status of machines and components in the factory.

### 3.6.5 Maintenance-Driven CPS Systems and Processes

Led by MMS, these provide semi-automated processes, tools and techniques for Self-Configuration and Self-Adaption that enable a PdM prediction.

### 3.6.6 Data Streaming & Analytics Infrastructure

Led by SENSAP and MMS, this comprises of all the data streaming and analytics infrastructure that will enable analytics both at the edge and at the cloud layers of the PROPHESY-CPS solutions.

### 3.6.7 LFML & HFML Components

Led by TUE, AIT and MONTRAGON, these components perform Data Analytics based on streaming data of the PHI UC (according to D2.4). The Low Frequency Machine Learning component resides on cloud and the High Frequency Machine Learning component resides on the Edge Server.

### 3.6.8 Use Case Instances

When observed from the specific viewpoint of UCs at JLR and PHI, Machine Learning and Statistical Data processing techniques for PdM (PROPHESY-ML) will be specifically developed to target the following KPIs among others (see Grant Agreement and relevant KPI deliverables):

- Maintenance interval
- Type of maintenance
- Spare parts on stock
- Average maintenance time of die
- First time right maintenance
- Second line support
- Lifetime of tools
- OEE

A **non-exhaustive** example of a **subset** of those (for understanding purposes) could be that in order to predict RUL, Repair time and optimal stock level, ML algorithms will be tried as follows (example):

**PHILIPS Use Cases:**

1. ML algorithm for RUL prediction on UC1 (1 wear part)
2. ML algorithm for RUL prediction on UC2 (5 wear parts)
3. ML Algorithm to predict repair time
4. ML Algorithm to predict optimal stock-level

**JLR Use Cases**

1. ML algorithm RUL Prediction of MAG Specht 600 Critical Parts (Use Case 4)
2. ML algorithm RUL Prediction of Cylinder Head Cutting Tools (Use Case 5)

## 3.7 Data Visualization SBs

A general distinction is made between data visualization on the one hand (including entities such as: dashboards, result tables, graphs etc.), and Augmented Reality (AR) service bricks on the other hand, which in principle consist of hardware & software for Remote Support Technology, Training and Knowledge Sharing.

The common base in Visualization and AR is the overall increased efficiency and safety of human-in-the-loop processes and they can both be the basis for knowledge sharing solutions.

Key parameters of Visualization beyond "presentation" and UX/UI, are the **frequency** of data presentation (i.e. how often a parameter is measured and refreshed and how often decisions must be made based on its value), the **role** of the person accessing the data and the **place** of presentation.

**Frequency** is inherently dependent on the index observed and the decision-making process. For instance, a KPI relating to RUL or some critical failure parameter at technical level might be monitored "live" on a screen in the proximity of the production line for imminent intervention by technicians. On the other hand, business and cost indices such as "Total cost of maintenance", "TCM over RAV", "Asset Utilization ratio Uptime/Downtime" are more appropriate to be graphs viewed by mid/high-level management for decision purposes and cost-benefit analysis, analyzed probably once per month/semester or even once per year.

**Role** refers to the access and decision rights of the person accessing the data. During visualization deliverables, roles on viewing, accessing, reviewing (at mid/high management level) and decision making will be addressed in detail.

**Place** within the same concepts of "per case application" will be provided at a machine, component and production system level, and on any needed display device, worker headset, mobile, tablet, pc screen, web portal or screen next to the machinery monitored, as needed per case.

DV Service Bricks identified are: Data Visualization Dashboard; PROPHESY-AR Remote Support; PROPHESY-AR Software (PHI-AR viewer).

### 3.7.1 Data Visualization Dashboard

Led by ICARE, the PROPHESY Data Visualization Dashboard, is a set of modules and components presented with appealing UX/UI on any needed display device, worker headset, mobile, tablet, pc screen, web portal, or even screen next to the machinery monitored, as each application requires. Their primary purpose is to visualize the defined KPI's, present diagrams, variance of quantitative measures, target to be achieved, and to visualize live data of the use-cases. It is expected that by switching the "input" i.e. the measured data stream

and the precise formula calculating the KPI (see KPI calculator tool), the dashboard can display in any of the various pre-designed templates the required graphs. The refresh rate, user role, place and frequency as defined above are to be defined per presentation case.

### 3.7.2 PROPHESY-AR Remote Support

Based on OCULAVIS "SHARE", the PROPHESY-AR Remote Support Technology and Training and Knowledge Sharing Platform, with remote and advanced visualization capabilities including AR, will guide maintenance employees in performing and completing maintenance processes, based on remote support from the machine vendor. In D2.4 its specific application is described for the instance of JLR UC6 using smart glasses to provide:

- Technical instructions for replacing key components / assembly
- Training and education
- Inform operators of damage precursors / imminent tooling failure

### 3.7.3 PROPHESY-AR Software (PHI-AR viewer)

Led by OCULAVIS, this service brick outputs AR based visualisations. It enables the integration of advanced visualization techniques based on augmented reality in the loop of PdM solutions as a necessary condition for reducing the maintenance costs. It will be created for Philips in PROPHESY specifically to be applied in the PHI UC, where the application requests data from the PROPHESY framework and displays it overlaying over the real tool as described in D2.4 and D5.1.

## 3.8 Data Collection SBs

PROPHESY envisions a novel CPS (Cyber Physical System) platform for predictive maintenance, which shall provide the means for diverse data collection, consolidation and interoperability, while at the same time supporting digital automation functions that will close the loop to the field and will enable "autonomous" maintenance functionalities. Beyond application-specific Connectors which are analyzed in the next chapter, the following prevalent service bricks in the Data Collection Layer are identified:

### 3.8.1 Data Collection & Analytics Middleware

Led by SENSAP and MMS, it refers to the middleware infrastructure that involves edge servers and devices to support data collection and analytics in PROPHESY-CPS platform

### 3.8.2 Interoperability & Data Sharing Middleware

Led by AIT, it refers to the middleware for transforming sensor data to semantically annotated formats and facilitate sharing and reuse of datasets across PdM stakeholders. It takes Sensor Data and Raw Data as input and returns Data Sharing, Semantic Formats as output.

### 3.8.3 Digital Models

Led by AIT, it belongs to the DC layer and the modelling category. It consists of agnostic digital models for representing PdM related datasets, takes Sensor Data and Raw Data as input and returns Data Schemas as output.

## 3.9 Connectors

As explained, connectors are not exactly "Service Bricks per se", but their presence is dictated by the specific "instance" of the use cases at hand. It is natural to categorize all connectors within the Data Collection (DC) Layer. The full table can be found in APPENDIX A2 and they refer to the UCs 1 to 6, excluding the Apache Kafka connector which has widespread applications and vast horizontal use in many PdM and general Industry4.0 and IoT applications.

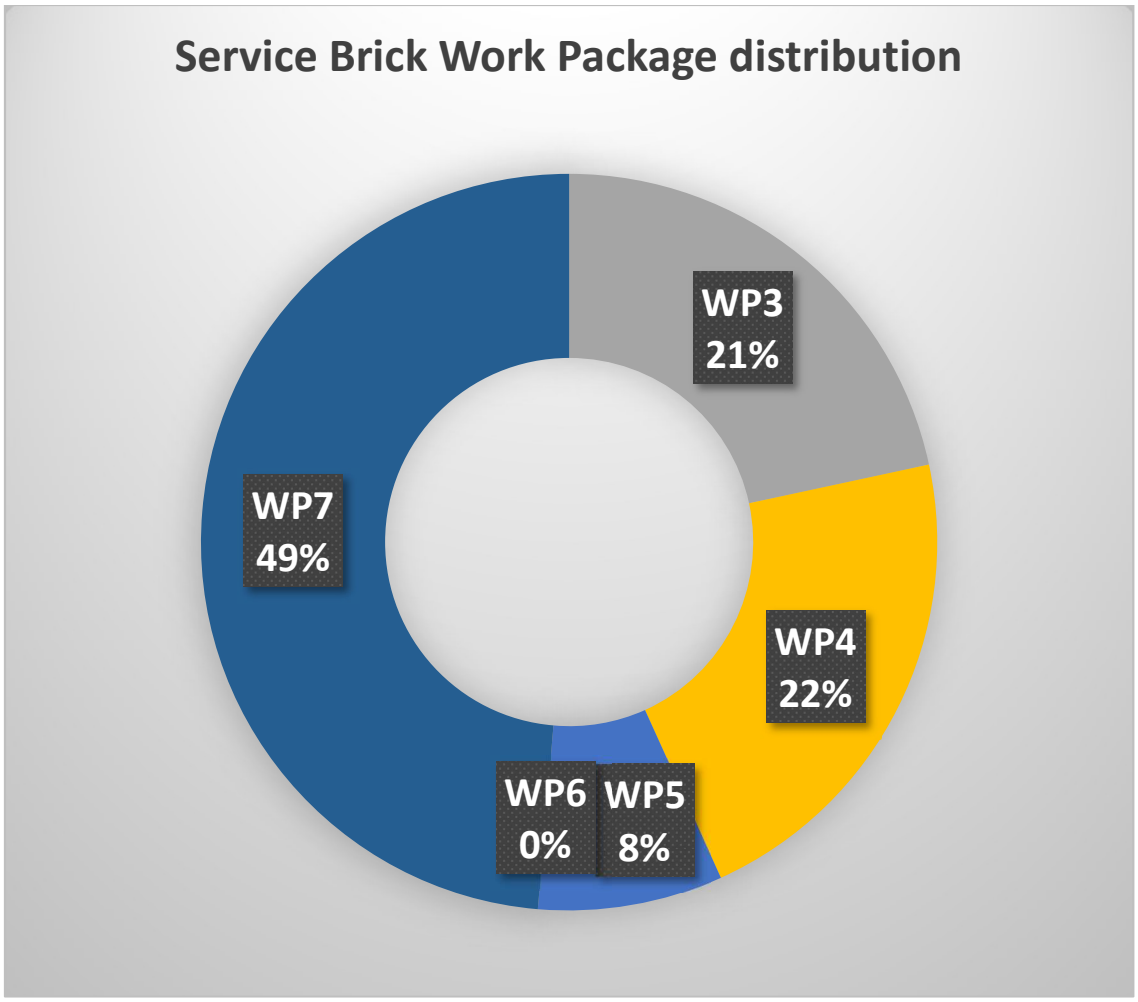


*Figure 5: Service Brick & Connector Distribution per WP*

If we were to consider both "core" service bricks and "connectors" and plot their distribution per Work package, we can observe the figure above. Notice that WP6 does not actually produce any service bricks in technical level, but it introduces the business chain of actions that connects all the building blocks into valuable higher-level entities such as solutions with a meaningful business target.

## 3.10 Tools

PROPHESY will produce the following **tools**; whose use is independent but complementary to Service Bricks. Their presence is obligatory since they are the connecting elements that make

aggregated service bricks into a "service" to work together meaningfully. Service Bricks are not just inanimate components of code, but they have a business logic that connects them for each application and the tools provide exactly that connecting property. Tools, are also independent in the sense that an interested 3rd party user can use them autonomously as services, and hence they are very important "exploitable assets" produced by PROPHESY. Their output alone can easily become an **independent SaaS offering** with substantial added value.

### 3.10.1 KPI Calculator tool

The Candidate Universal PdM KPI list presented in chapter 6.1.3 and appendix 3 of the present deliverable, is an elaborate work of PdM consulting nature conducted by INTRA, ICARE and AIT, but is only the beginning of the process concerning KPIs. It must be clarified that this is a much broader list, not necessarily applicable to the 2 demonstrators, but more of a "universal PdM consulting" nature. Implementing only parts of it, or its entirety within the KPI calculator tool, is only a matter of decision, based on the needs, as in the end adding more calculation formulas a ready tool is just a revision process.

The subset of applicable KPIs specifically for the UC instances have initially been defined as addressing the following list:

- Maintenance interval
- Type of maintenance
- Spare parts on stock
- Average maintenance time of die
- First time right maintenance
- Second line support
- Lifetime of tools
- OEE

D6.3 will present the full specifications of the KPI calculator tool, the KPIs Specification and their Tracking. This subset will not only be implemented in the KPI tool, but its visualization (ex. Through dashboards) will also be integrated.

As far as this deliverable is concerned, The KPI Calculator Tool has the additional benefit of being a stand-alone tool that any interested 3rd party can evaluate through the PROPHESY Ecosystem, so it is an "exploitable asset" of the project on its own and is not strictly confined in the Use cases (UCs) of the Demonstrators. An example of its envisioned stand-alone use is presented in chapter 6.

**KPI Calculator input required**: Formula, Source of Data, format of Data, Units of Measure, Target, Applicability (if the UC deems the particular KPI to be important)

**KPI Output**: Graphical and numerical, frequency of refresh and calculation, target to be reached, other statistics as needed (ex. How close did we reach, what variances have been observed etc.), as jointly developed with the DV Dashboard that will present graphical representations of its output.

**Further division**: As suggested by PHI and ICARE based on their experience, and as it will be elaborated in the relevant deliverable on KPIs, PROPHESY wishes to further distinguish between leading KPI's (to STEER a process) and lagging KPI's (to MONITOR a process), as suggested by the literature (Ex. dashboard insight [22])

### 3.10.2 Cost Benefit Tool

Likewise, the Cost Benefit Tool is the logical "consequence" tool i.e. it takes the output of the KPI tool as input. Although it will be fully specified in D6.5, we hereby present its brief mathematical concept:

**STEP 1)** Let the Solutions offered be named "SOL(1), SOL(2), … SOL(i)"

**STEP 2)** Let the KPIs selected as being applicable on "SOLUTION_i" from the Candidate KPI list (see Appendix A3), to be: KPI(1,i), KPI(2,i), … KPI_(j,i) ("i" being the solution number and "j" being the KPI index i.e. the second column of Appendix A3 referring to the number of the KPI) as defined upon use case analysis and business consulting (for instance: OEE increase, RUL, or Downtime or whatever similar is chosen.)

**STEP 3)** Define the **Benefit Bi** of a turn key solution SOL(i) as a function of the "delta" of KPIs, i.e. their value before and after the application of the Solution(i). (in plain terms the benefit due to KPI improvement)

Bi = Benefit-of-Turn-Key-Solution i = F[(KPI1i, KPI2i,...,KPINi),

In simple terms, let the "delta" i.e. the KPI improvement be translated into monetary terms according to the beneficiary plant's management knowledge. An example would be "increasing the Remaining Useful Life or the MTBF by a month would incur savings of X EUR" or alternatively, "A timely prediction of the wear level of a critical part, leading to a well-planned maintenance action, saves Y minutes of downtime, leading to Z EUR in monetary terms as calculated by machinery output in cost/monetary terms"

**STEP 4)** Define the cost of a turn-key solution as a function (probably a sum) of service bricks, building blocks and supportive services used in SOL(i) i.e.

$$\textbf{Ci = Cost of turn-key solution i} = \sum_{i=0}^{n} \boldsymbol{CSBi} + \sum_{j=o}^{k} \boldsymbol{CASj}$$

Where CSBi (i=0...n) the cost of the ith service brick that is contained in the turn key solution and CASj the cost of the jth (j=0...m) complementary Augmented Service AS (training, technical support etc) used in the solution.

**STEP 5)** The Cost-Benefit calculator and the PROPHESY SOE shall collaborate to calculate the cost benefit ratios Bi/Ci, will consider Sensitivity Analysis (through "perturbations" i.e. variations in inputs and how they affect outputs), and might attempt to even suggest the "optimal" (maximum)

$$MAX\ (^{Bi}/_{Ci})\ \text{(i=0...k)}$$

i.e. the turn key solution (or solution configuration) that maximizes the benefit/cost ratio, if more than one solutions are technically applicable.

**Requirement**: It shall need to be able to have the information (or a close estimation) about the cost and other monetary values as input, since by definition all cost-benefit, ROI, NPV, Payback and other well-known indices take monetary values (and time frame of inflows/outflows) as input. In that sense, it has been foreseen that: benefits in direct or indirect monetary terms (example savings, profits etc.) need to be provided by the beneficiary plant in charge, whereas costs of Service Bricks and Tools shall be provided by their respective owners/suppliers in collaboration with the entities responsible for their deployment at UC premises. The beneficiary plants have thankfully the historical expertise, inside business knowledge and manufacturing process knowledge in order to refine the benefits, as these will be elaborated in WP7.

**Inputs to Cost-Benefit Analysis Modules**: The cost-benefit analysis components will take as input a set of parameters that are associated with the costs a PROPHESY deployment (e.g., costs of software licenses, costs of developers' resources, hardware and equipment costs, training and consulting costs, deployment costs), as well as with estimates of the anticipated benefits (e.g., maintenance savings, increased OEE, savings on inventory costs, saving on maintenance engineering costs). These inputs will be provided in either of the following two ways: (i) Based on data entry processes from maintenance and/or business experts; (ii) Calculated based on data from PROPHESY systems and databases.

**Output of the Cost-Benefit Analysis Modules**: The output of the cost-benefit analysis tool will also include: (i) Bi/Ci, MAX Bi/Ci, Capital Budgeting Indicators (e.g., ROI (Return-on-Investment), IRR (Internal Rate of Return) and Payback Period); (ii) The estimated total (annual) savings resulting from the predictive maintenance deployment and the Total Cost of Maintenance (TCM) break-down. In other words, if PdM (predictive Maintenance) increased, CM (corrective) and UM (unplanned maintenance) decreased, whether PM (preventive maintenance changed (hopefully decreased) and what happened to their total sum i.e.

Total cost of Maintenance per Asset: TCM=PdM+PM+CM+UM+ Cost of maintenance training.

An interesting result might also occur if for instance: Total TCM is increased but overall efficiency is improved and TCM per asset output is improved even further (see Appendix 3 index 1.3). This could imply that although one Economic KPI is intentionally reduced (TCM is now more expensive), another more important KPI (asset output/ TCM) is improved, i.e. an educated business decision of intentionally raising maintenance cost to achieve even better output from the machine (positive benefit overall).

### 3.10.3 PROPHESY-SOE

One of the key innovations of PROPHESY is the creation of a PdM service optimization engine (PROPHESY-SOE), which will enable composition of optimal PdM solutions based on the capabilities provided by PROPHESY-CPS, PROPHESY-ML and PROPHESY-AR. Service optimization aspects will consider the whole range of factors that impact PdM effectiveness.

Optimization can assume the viewpoints of cost, speed of result prediction, accuracy of results, robustness, frequency of follow-up, and applicability (as not all solutions are obviously fit for all problems, so a comparison of “alternatives” will be in order). The PROPHESY SOE precise specifications and analysis is out of scope for now as it will be the very next deliverable in the WP6 chain, which is D6.3. The present deliverable constitutes its main input.

### 3.10.4 Self-Adaptation and Self-Configuration component

The Self-Adaptation and Self-Configuration component transforms the results of the data processing tasks and processes into adaptations and configurations to be fed back to the physical assets through the PROPHESY-CPS. It has been chosen to be classified as a “tool” rather than a “service brick” due to its broad use that it can be effective beyond the instances of the 2 demonstrators / 6 use cases. Note: In case self-adaptation or self-configuration of physical assets is not allowed, due to strict process boundaries or safety regulations, human interaction is needed to adapt or reconfigure the asset. For this case, the Prophesy-DSS is designed to provide clear and easy instructions for the operator.

# 4 Service Bricks as a Component Development Baseline

## 4.1 Technical Baseline

As explicitly described in the definitions section, Service Bricks should be viewed as constituent "building blocks", which when combined with tools and services should be able to offer solutions on cutting edge PdM applications. Their business scope is the "first step" in the WP6 chain. Yet, the SB and connector list (depicted in Appendices A1 and A2) also encompass substantial partner knowledge and collaboration effort within them. Hence, it has recently been decided that they should also serve as the PROPHESY partner "reference baseline" when following up both architectural as well as component development issues. At the time of the submission of the present deliverable, the component development baseline is based on the Service Brick and Connector list, which has reached its 12th revision in September 2018 (unanimously accepted by all partners). It is currently actively managed by INTRA with the expert assistance of FHG, and it is updated in the collaborative space of the PROPHESY Redmine portal. It hence also serves (secondarily) as a general go-to reference for most WP3, WP4 and WP5 technical meetings.

## 4.2 Packaging and Deployment

The implementation of the Service Bricks involves the usage of different programming languages and managing different integration tools & frameworks. To deal with the deployment and orchestration of such diverse technologies these Service Bricks need to be encapsulated in self-contained environments benefiting from quicker deployments, scalability and closer parity between the different environments.

**Containerization** (also known as Operating-system-level virtualization) achieves that encapsulation. With containers, isolation is done on the kernel level without the need for a guest operating system (and thus pre-defining resources that often are not utilized). This leads to more efficient, fast and lightweight solution. Containers are quite flexible since even the most complex applications can be containerized and offer great portability, they can be built locally, deploy on the cloud (or in single server) and run anywhere. Moreover, containers are stackable. Hence, a Service Brick can be composed by several others, and similar ones can be bundled in the same container. Several solutions (example docker) are currently evaluated as candidate containerization solutions, yet comparison and justification of choice is still pending and these will be analyzed in WP3 deliverables.

# 5 PROPHESY Solution Composition Business Model and Decision Making

As far as the PROPHESY SOE, and the solution creation through building blocks are concerned, the following aspects are noteworthy from a business point of view.

## 5.1 What is the Business offering of Service Bricks?

As introduced in previous sections, interested 3rd parties / members may visit the PROPHESY ecosystem/Marketplace/Multisided Platform and seek "solutions" and composition of "service bricks" for two distinct reasons:

1) They already have a Predictive Maintenance related problem seeking solution, and they more or less have concluded some specific business target they would wish to achieve within their line of business, or
2) They are genuinely interested in novel services of PdM, cutting edge Analytics, Machine Learning, Data Collection, Visualisation, Augmented Reality and other PROPHESY related activities, and seek to evaluate what PROPHESY service bricks and PROPHESY-SOE could do to assist them. In the latter case, PROPHESY will help them clarify the ideas of which specific business target or quantitative index they might be able to pinpoint. In plain terms, PROPHESY service bricks will be "evaluated" and the target may be formulated afterwards.

Service Bricks, Tools and other building blocks are not inanimate, secluded entities. As the definition of chapter 2 clearly states the scope is" to combine them into an aggregated entity (up to the highest level of a turn-key solution) that can provide to an end-user or beneficiary within the wider Predictive Maintenance schema, a **desired result** or a **conclusion** towards a **business decision".** In the next section we apply these concepts. The first point is to define tangible and measurable quantitative metrics.

## 5.2 Select Maintenance Quantitative Target & Business KPI

The first step towards the design of any turn-key solution is the precise definition of what exactly is the "target" to be achieved, which is a process initiated by an expert consultant (one example would be ICARE at our demonstrator plant), based on the experience and knowledge of the beneficiary plant. Hence, following business and operational analysis, a solid quantitative metric of success must be defined to be reached and measure results against it. Specific quantitative or qualitative indices can take the form of any KPI or FMECA (Failure mode, effects and criticality analysis) or RAMS quantitative target to be achieved as clarified by the PdM consultant based on the business needs of the client/beneficiary manufacturing plant.

Moreover, any related business or operational metric concerning management decisions at upper/mid/ or low level management, such as cost cutting, time optimization, Asset efficiency, Remaining lifetime of equipment, operational indices related to maintenance,

critical failure part identification etc. as dictated by the end-user as being essential and requiring PdM optimization.

## 5.3 The Universal KPI candidate list for PdM applications

In that scope, a very thorough analysis has been conducted by AIT, ICARE and INTRA on Predictive Maintenance and general Maintenance consulting literature, usecases, whitepapers and applications, in order to decipher the most common metrics used by leading corporations, reference publications on the field, State-of-the-art applications on PdM and Smart Factory from world class manufacturers such as Hitachi, General Electric, Toyota et al, as well as leading consulting companies such as Deloitte , McKinsey, PCA, Lifetime-reliability Australia and others (see References [8]-[21])

The output of this elaborate work is the "Universal PdM KPI list" which is presented in Appendix A3. We have gathered and categorized most common KPIs used in Predictive Maintenance and general Maintenance situations and have tried to divide them according to "level of management involved", frequency of observation, metric, unit and category. Moreover, we have grouped them into a WBS tree-like structure with levelled numbering into common groups.

| Category of KPIs | Quantitative Metric | Units of Measure | Important to | Frequency |
|---|---|---|---|---|
| **ECONOMIC** | Cost, Savings and Benefits, TCO, TCM, RAV etc. | MONEY | Upper-Managerial Level | Seasonal / Yearly |
| **OPERATIONAL EFFICIENCY & ASSET UTILIZATION** | Downtime/Efficiency/ Remaining Useful Lifetime RUL, replenishment, etc | TIME | Mid-Managerial Level | Monthly / Weekly |
| **MAINTENANCE METRICS** | MTBF, Frequency, Durations, Root Cause ID, etc. | INDICES | Operational Level | Daily/ "Live" |

*Table 2: Universal PdM KPI Categorization Table*

This list although not perfect (hence the usage of the word "candidate"), can still be considered quite complete (hence the usage of the word "universal") in the sense that it tries to encompass all possible categories of PdM KPIs at all possible managerial levels, units of measure and frequencies that a "general PdM case" would have to consider, based on the paradigm of a multitude of similar cases that we have reviewed. Hence its value lies in the fact that it is obviously not restricted the UC specific nature of the 2 demonstrators JLR and PHI. Being a "general purpose" tool, it can become the basis of a business consulting service for 3rd party beneficiaries in the future during sustainability stages, were only the applicable lines of the table (KPI entries and categories) are selected each time for each case, upon review. For instance, in our 6 "use case instances" at JLR and PHI, the indices of operational efficiency and asset utilization selected can be the Universal PdM KPI table entries: 2.1, 2.2, 2.3, 2.10, 3.1.4 and 3.3 while the Cost-Benefit Tool (to be elaborated in D6.5 and D6.6) is

expected to address the notions shown at table entries: 1.1, 1.3, 1.6, 1.7 and 1.9. (See Appendix A3). These will become finalized in the second revision of the KPI deliverable D6.6 but the main notions are already agreed and put in place, while they are also included in the Universal KPI list.

## 5.4 Follow-up the target and evaluate the result

From a business point of view, the overall methodology is quite self-explanatory and resembles the following steps used in most similar business cases:

1. Define applicable KPI's from the Universal PdM KPI list
2. Refine them according to beneficiary internal knowledge and experience
3. Provide the means for calculating the KPI's (measurements, calculations, other forms of data and precise formula)
4. Specify the sources of data for the KPI calculations
5. Select Data Collection SBs and application specific Connectors to deploy them
6. Build the service or solution through the PROPHESY SOE
7. Apply ML and DA services
8. Employ the KPI Calculator tool (D6.3) and Visualize results through DV
9. Revise through iterative feedback, business training, technical consulting and support
10. Employ "Cost-Benefit" function D6.5, compare Benefits and Benefit/Costs to reach final conclusions and business decision

These concepts will be further elaborated in the dedicated D6.3 "KPIs Specification and Tracking" and together with D6.5 "Cost-Benefit Analysis" will provide specifications on the homonymous tools.

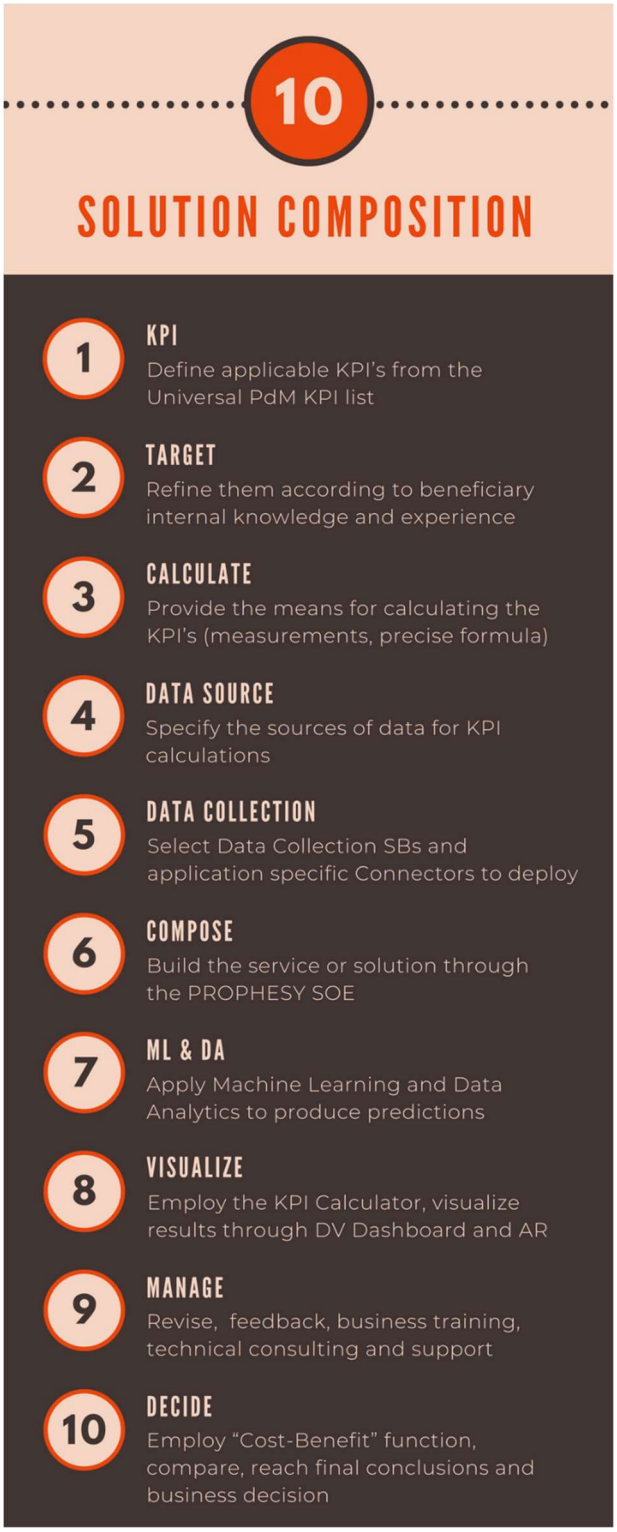


*Figure 6: Solution Composition Methodology*

## 5.5 Best Practices and Maintenance Benchmarks

An example of the above process follows below. When implementing the above general theory into Use case practice, specific KPIs (out of the universe of all possible PdM KPIs that could possibly be used) will be selected based on plant historical knowledge and specific technical expertise. Also specific targets (i.e. benchmarks) will be selected for the above. In the following table (kind courtesy of PHILIPS) a specific KPI and benchmark pairing is depicted, currently used by the tooling maintenance department. Note that "turns ration of spare parts" and "re-work" are defined here. More technical details can be found on D2.4 "Complex Demonstrators Specifications". Maintenance Benchmarking is also covered in [23] and several similar concepts have been implemented in our case.

| Best Practices Maintenance Benchmarks | |
|---|---|
| **Category** | **Benchmark** |
| **Yearly Maintenance Cost:** | |
| Total Maintenance Cost/Total Manufacturing Cost | < 10-15% |
| Maintenance Cost/Replacement Asset Value of the Plant and Equipment | < 3% |
| **Hourly Maintenance Workers as a % of Total** | 15% |
| **Planned Maintenance:** | |
| Planned Maintenance/Total Maintenance | > 85% |
| Planned & Scheduled Maintenance as a % of hours worked | ~85-95% |
| **Unplanned Down Time** | ~0% |
| **Reactive Maintenance** | < 15% |
| **Run to Fail (Emergency + Non-Emergency)** | < 10% |
| **Maintenance Overtime:** | |
| Maintenance Overtime/Total Company Overtime | < 5% |
| **Monthly Maintenance Rework:** | |
| Work Orders Reworked/Total Work Orders | ~0% |
| **Inventory Turns:** | |
| Turns Ration of Spare Parts | > 2-3 |
| **Training:** | |
| For at least 90% of workers, hours/year | > 80 hours/year |
| Spending on Worker Training (% of payroll) | ~4% |
| **Safety Performance:** | |
| OSHA Recordable Injuries per 200,000 labor hours | < 2 |
| Housekeeping | ~96% |
| **Monthly Maintenance Strategies:** | |
| Preventive Maintenance: Total Hours PM/Total Maintenance Hours Available | ~20% |
| Predictive Maintenance: Total Hours PdM/Total Maintenance Hours Available | ~50% |
| Planned Reactive Maintenance: Total Hours PRM/Total Maintenance Hours Available | ~20% |
| Reactive Emergency: Total REM/Total Maintenance Hours Available | ~2% |
| Reactive Non-Emergency: Total RNEM/Total Maintenance Hours Available | ~8% |
| **Plant Availability:** | |
| Available Time/ Maximum Available Time | > 97% |
| **Contractors:** | |
| Contractors Cost/Total Maintenance Cost | 35-64% |

*Table 3: PHILIPS Best Practices and Maintenance Benchmarks*

# 6 Examples of Stand-alone Services

It must be clear by now that PROPHESY is not restricted in the validation of its seamless operation through the 6 use cases of the 2 demonstrator factories alone. PROPHESY has a much broader vision and offers vast opportunities through the combination of its constituent components into solutions that can help the project sustain itself beyond its lifetime.

Indeed, the principal case is when various constituent components are combined into a "solution" for example through the PROPHESY SOE and a careful combination of SBs. PROPHESY-SOE answers the question: How to create Integrated Solutions & Services, in-line with manufacturers' needs to the strict specification of what a KPI dictates and to follow up the visualized results. Yet, it must also be stressed that some of the constituent components are inherently a "standalone service" on their own. Specifically:

## 6.1 Stand-alone Application Services

### 6.1.1 Exploitation/Simulation Tools as a Service

A very attractive feature for the PROPHESY ecosystem can be the exploitation/simulation tools based on PROPHESY service Bricks. For example a 3rd party user may select a specific data analytics algorithm (for instance a mining algorithm within the PROPHESY ML), provide (upload) the necessary inputs as clearly and concisely stipulated in the support section of each SB, (for instance the multi-dimensional dataset, the support thresholds, confidence levels, and other parameters in a specified format), and receive results **as a Service** (for instance predicting upper-bounds in the Remaining Useful Life of a part, by discovering all non-dominated rules that indicate that a set of rarely occurring pre-conditions triggers a maintenance need).

This has extremely important added value because it can even become the basis for exploitation and monetization, as an independent parallel service offered to members of the ecosystem. Visitors provide data sets and other parameters (for instance comma delimited texts). They receive a full report (for example non-dominated rules that specify values for a single attribute of a single consequent item) that helps them draw conclusions in their specific application field (Strictly PdM or even wider). This is a typical example of an "integrated service" based on a "single service brick" (in this case the PROPHESY ML SB belonging to the DA layer).

### 6.1.2 What-if Analysis

Many useful business questions can be formulated in the form of "What-if-Analysis", since in most real-world cases a solution goes beyond just providing an answer, but the "answer" must also be "robust" and resistant to "perturbations".

As an example of a "What-if-Analysis" within our scope, we can again select the PROPHESY ML toolkit which provides 7 broad categories of algorithms (as presented in chapter 3.5.1).

Here, we do not just seek a quantitative answer to a KPI through DA algorithms. We analyse the answer's robustness and useful extended questions arise, with very appealing application and direct benefit to 3rd party business/manufacturing users:

- What happens if a parameter in a machine (for instance hit-rate or torque) is changed, and how is RUL of the critical component affected? This is extremely important for operational fine-tuning and optimization of equipment life-time.
- What perturbations or variations arise to parameter A, if parameter B were to be changed within the multidimensional dataset? Is the answer sensitive to change? Is there an optimal point cost-wise?
- Which of the 7 categories of ML and DA algorithms is more suitable for our "specific" case? Which of them yields the most consistent results for this particular application, and "how" (or even "if at all") others converge to the same values?
- What if the process were to be changed, the KPI targeted were to be slightly modified or the confidence intervals and other parameters were to be "adjusted"? Is the prediction still reliable? Is the prediction produced faster? Is it becoming more accurate and can we verify the prediction by physical removal of the failed part to see that it indeed needed replacement as predicted?
- How would a variance (delta change) in a KPI (as input) affect the Cost Benefit function (as an output), and is it worth it investment-wise?

These questions are invaluable in business scope for any Industrial Maintenance case, and at the same time they are quite easy to implement technically, once the PROHPESY ML toolkit is complete, as the What-if-Analysis is basically simplified to formulating the appropriate question and "running" the algorithms as a Service through the ecosystem several times with different parameters as multivariable input. Most importantly, this service offers the additional option of even possibly charging/monetizing through their use at a later stage after the projects lifetime (per use or per dataset or per computational load etc.) and hence offers added value as a standalone offering.

### 6.1.3 KPI Calculator & Cost Benefit Calculator Tools

In chapter 3.10.2 we have presented the first technical specifics of these tools. In this section we pay attention to the fact that these PROPHESY tools are also stand-alone independent builds, which have architecturally been selected to be of general purpose and not vendor/use-case/instance specific. Taking into account the fact that they are of intrinsic broad use in many business environments as they calculate widely accepted quantitative measures such as cost/ROI/monetary benefit/time and efficiency metrics etc., we consider them to be very important PROPHESY exploitable assets and we envision a simple application within the PROPHESY ecosystem to provide an interface API for an independent SaaS offering of their remote use by 3rd parties, that will bring substantial added value to the project.

After all, the tools as described in Chapter 3, take input in a predefined format, or are provided with the sources of data, specify precise formula, take costs into account, present the measurements, calculations, and in the end provide invaluable information to any 3rd party

user wishing to try them in the form of: Capital Budgeting and ROI Calculation, Optimization (MAX Cost/Benefit per solution, comparison of benefits as in the example of chapter 3.10.2, perturbation and variance analysis, graphs, etc.)

## 6.2 Augmented Business Services:

The PROPHESY ecosystem realizes the need that turn-key application services must always be complemented by the human effort of specialized consultants, PdM professionals, experienced integrators Data Collection and Analytics experts and other qualified human resources in their respective line of expertise. Roles within the value chain will also be properly addressed within D8.7 concerning business exploitation. Augmented Business services can range among: Technical support, Technical Consulting, Business Consulting, KPI and Cost benefit formulation, needs and requirements formulation, prediction formulation, follow-up and revision, decision support in collaboration with beneficiary management, Training services (including Training material) etc. The PROPHESY ecosystem will be in the position to provide:

### 6.2.1 Technical Support Services

Support on the use & deployment of all PROPHESY technical components, including all technical documentation

### 6.2.2 Business Support Services

In the previous chapter we have introduced various examples of business support services towards end users/beneficiaries, ranging from needs and requirements formulation, Capital Budgeting and ROI Calculation, What-if Analysis, sensitivity and perturbation analysis etc.

### 6.2.3 Training and Consulting Services

Interested 3rd parties and ecosystem members/ stakeholders will have access to specialized training through the appropriate personnel of partners according to each area of expertise. Training can be offered among others on:

#### *6.2.3.1 General Training on Predictive Maintenance and KPI selection*

Consulting on KPI definition as per Appendix A3 and chapter 5.2, as well as general training on PdM issues by partner experts can be provided and familiarized with.

#### *6.2.3.2 Training on PROPHESY Solutions and Services*

It is expected that all constituent components of PROPHESY will be accompanied by a technical article and possibly a ppt presentation when needed. Moreover, aggregation of service bricks into turnkey solutions such as the UCs will be analytically described. These can be the basis for training material.

#### *6.2.3.3 Consulting on Solution Design*

As above but focused more on the PROPHESY SOE (see D6.3) and the methodology presented in chapter 5.4

#### *6.2.3.4 Consulting on Solution Migration*

A prominent example that specialized experts of the consortium partners can provide valuable consulting, is assistance to interested 3rd parties in the transition from corrective/preventive into predictive maintenance, as well as comparison of benefits as described in chapter 3.10.2 where it was demonstrated that increasing the PdM and TCM costs, might actually decrease the overall Asset Cost and boost efficiency and OEE.

# 7 Service Bricks and Building Blocks usage within the Ecosystem

## 7.1 Building Blocks presented in the Ecosystem Platform

One of the visions of PROPHESY is to design and develop a **service-brick oriented** ecosystem through a web-based Multi-sided-Platform (MSP). Within the PROPHESY ecosystem whose specifications are detailed in D2.5, all building blocks will not only be presented but will also be hierarchically accessible for evaluation, aggregation and for use within solutions.

The uttermost scope when the consortium carefully selected the PROPHESY architecture to include entities such as "building blocks", "service bricks" and PROPHESY-SOE, was to ultimately provide an integrated PdM solution platform built of interchangeable, complementary components. Hence it is evident that their presentation, dissemination, evaluation by 3rd parties and expansion should come through the ecosystem and its community. Ideally, it could achieve a "Critical-mass" community of members.

Apart from the obvious function that the ecosystem should be a "presentation hub" in a coherent manner in the form of a marketplace-like platform including all the assets, service bricks and other building blocks, the real challenge will be to achieve the following targets:

- To satisfy the "Demand-side Stakeholders" i.e.: manufacturers, machine vendors, PdM and Industrial IoT services developers, IoT and I4.0 solutions integrators, ML specialists, Maintenance specialists, affiliated business entities to partners, and all other stakeholders seeking either PdM solutions and tools, or participating in the ecosystem to learn about its assets, and validate/evaluate them
- To satisfy the "Supply-side Stakeholders", not restricted to project partners but extended to all 3rd party contributors who enhance the ecosystem through submission of additional content and complementary software modules. Even plain comments on evaluation of existing service bricks are an invaluable contribution that PROPHESY wishes to receive.
- To attract a significant number of participants (**critical mass**) and hence to increase the value offered to manufacturers, PdM solution integrators and other stakeholders. PROPHESY in general is strongly inclined positively towards open-source (by definition preferred in terms of critical mass creation) when company royalties, safety and security issues as well as previous background IPR, permit so.
- To provide a liaison point for similar initiatives with well-established related platforms existing communities and ecosystems, communities where partners are actively involved and research /commercial i4.0 and PdM platforms
- To facilitate sustainability, enhancement and improvement of the PROPHESY services following the end of the project's lifetime.

## 7.2 Ecosystem Platform Components

Although this section is addressed explicitly in detail within D2.5, in the scope of this chapter we are only interested in the following distinction of components:

### 7.2.1 Operational Components

These include all "expected" operational features of any complete and friendly portal/ecosystem -in general- irrespective of use within the PdM context. Hence they are beyond the scope of this document (see D2.5), but they typically include entities such as: Registering Participants & Business Entities, Authentication and Authorization, Localization, Knowledge base, Manage and tracking registered services etc. They only offer the "infrastructure" for the operation of the ecosystem.

### 7.2.2 Presentation of PROPHESY Building Blocks

The scope is to provide an "inviting" way to 3rd party members, for them to try PROPHESY services for their needs, evaluate its building blocks and architecture and learn what PROPHESY has achieved in a user-friendly mode. Hence these include features that "invite to try" such as:

- Search and discovery of service offerings
- Catalogue Publishing of service bricks and building blocks
- Review and rating of service offerings (based on previous user's experience)
- Provision of recommendations
- Solution Presentation
- Services Presentation

### 7.2.3 Service-Offering Components

These are the core offering, since they answer the business question "What can PROPHESY and its building blocks do for me". These are:

- Access to PROPHESY Tools for evaluation and use
- Access to PROPHESY Service Bricks for evaluation and use
- PROPHESY SOE
- Exploitation/Simulation Tools
- Training, consulting and technical support services
- KPI definition and KPI Calculator
- Cost Benefit Definition and Cost Benefit Calculator
- Libraries
- Developers' support services
- Informational and support material

### 7.2.4 Related Platforms & Prototype Implementation Candidates

Wider dissemination plans (see D8.2) and Strategy guidelines on distribution channels (see D8.7) have narrowed down the following related platforms beyond the PROPHESY portal as Ecosystem implementation candidates and as platform affiliations (bringing a critical mass of registrants): FAR-EDGE (www.edge4industry.eu) (sharing common partners with PROPHESY

and common research focus on IoT for Industry) with which a common participants and registrant database is envisioned and has already been agreed, IoT Catalogue (www.iot-catalogue.com) (an accomplished MSP privately owned by UNPARALLEL), the expanded INTRASOFT Sandbox Exploitation Platform for solution deployment, the FoF cluster for dissemination reasons et al. In order to disseminate the "success stories" of PROPHESY to a wider audience, it has been proposed by WP7 leaders that (after significant registered sign-ups and critical mass creation) to demonstrate numbers/graphs showing number of users, cumulative and average cost savings, average OEE increase, average downtime reduction, etc.

# 8 Conclusions and Future Outlook

The quintessence of PROPHESY Architecture and PROPHSEY SOE, lie in the segmentation of "building blocks" in the form of Service Bricks, Connectors, Tools and Services (both application-wise and business-wise) which can be properly combined into higher level entities to formulate a solution. The 2 demonstrator plants with the 6 use-cases are not only validation points, but they also are considered "instances" of a much wider scope of PROPHESY, to exhibit its ability to create integrated PdM Solutions and Offerings as a Service. The project envisions a service-brick oriented Ecosystem with a twofold purpose:

- At first to present these constituent components coherently for evaluation and wider use, and
- to concurrently begin a community of members beyond the project stakeholders that will enhance the PROPHESY ecosystem both as a
    - demand-side (asking for solutions and services) as well as
    - supply-side (offering augmented and complementary components, enhancing existing ones, or just evaluating and rating existing ones as 3rd party users).

Within this deliverable, definitions of the building blocks have been presented, their layers, categories and specifications have been rendered, deployment and packaging has been addressed, but most importantly a business viewpoint has been given. Solution composition, PdM KPI definition and Stand-alone services have been demonstrated. Finally the ecosystem that will encompass the building blocks and present them in a coherent manner to the community has been manifested as the distribution channel of these Service Bricks (SBs).

The constituent building blocks of PROPHESY as outlined in this deliverable are the basis of the WP6 cycle: (select, combine, calculate metric KPI, calculate the cost-benefit, revise and provide feedback). This was depicted in chapter 5 and will be fully demonstrated within the series of the next deliverables of WP6. Furthermore, this process will initiate WP7 evaluation during the "instances" of the use cases and will additionally formulate the Assets to be exploited during sustainability and dissemination (WP8).

In the next version of the present deliverable in one year from now, the technical details of the Service Bricks and the other components will have reached higher maturity levels so as to also be able to define explicit inputs and outputs, as well as precise technical specifications, packaging and deployment aspects.

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# Appendix A

## A.1 Core Service Bricks Table

| Service Brick | Introduced By | WP | Deliverable | Category | Layer |
|---|---|---|---|---|---|
| **Security, Trustworthiness and Data Protection Framework** | MONDRAGON, FHG | WP3 | D3.11, D3.12 | Security | SEC |
| **PROPHESY-ML Toolkit** | AIT, MONDRAGON, TUE | WP4 | D4.7, D4.8 | Data analytics | DA |
| **QARMA Machine learning algorithms** | AIT | WP4 | D4.7, D4.8 | Data analytics | DA |
| **Data Mining Techniques** | MONDRAGON | WP4 | D4.5, D4.6 | Data analytics | DA |
| **Data Analysis & Fine-Tuning** | TUE | WP4 | D4.5, D4.6 | Modelling | DA |
| **Maintenance-Driven CPS Systems and Processes** | MMS | WP3 | D3.9, D3.10 | Data analytics | DA |
| **Data Streaming & Analytics Infrastructure** | SENSAP, MMS | WP3 | D3.7, D3.8 | Data analytics | DA |
| **ML Algorithm: Remaining Useful Life** | PHILIPS | WP7 | D7.3, D7.4, D7.5 | Data analytics | DA |
| **ML Algorithm: Repair Time prediction** | MAG | WP4 | D4.3, D4.4 | Data analytics | DA |
| **ML Algorithm: Optimal Stock-level prediction** | MAG | WP4 | D4.3, D4.4 | Data analytics | DA |
| **LFML Low Frequency Machine Learning component** | AIT, MONDRAGON, TUE | WP4 | D4.3, D4.4 | Data analytics | DA |
| **HFML High Frequency Machine Learning component** | AIT, MONDRAGON, TUE | WP4 | D4.3, D4.4 | Data analytics | DA |
| **Machines and Tools Models for Data Analytics** | MAG | WP4 | D4.3, D4.4 | Modelling | DA |
| **Digital Models** | AIT | WP3 | D3.3, D3.4 | Modelling | DC |

| | | | | | |
|---|---|---|---|---|---|
| **Interoperability & Data Sharing Middleware** | AIT | WP3 | D3.3, D3.4 | Middleware | DC |
| **Data Collection & Analytics Middleware** | SENSAP, ART | WP3 | D3.7, D3.8 | Middleware | DC & DA |
| **PROPHESY-AR Remote Support Technology and Training and Knowledge Sharing Platform (based on oculavis SHARE)** | OCULAVIS | WP5 | D5.6, D5.7 | Visualization | DV |
| **PROPHESY-AR Software (PHI-AR viewer)** | OCULAVIS | WP5 | D5.6, D5.7 | Visualization | DV |
| **PROPHESY Sensor Data Collection** | ICARE, MMS | WP3 | D3.5, D3.6 | Data collection | DC |
| **Automatic Data Collection** | ICARE, MMS | WP4 | D4.1, D4.2 | Data collection | DC |
| **Adaptation Management** | FHG | WP3 | D3.4 | Middleware | MGMT |
| **Administration Shell Manifest + Flows** | NOVAID | WP3 | D3.4 | Middleware | MGMT |
| **Administration Shell API** | UNPARALLEL | WP3 | D3.4 | Middleware | MGMT |

*Table 4: Core Service Brick Table*

## A.2 Connectors Table

| Service Brick | Introduced By | WP | Deliverable | Category | Layer |
|---|---|---|---|---|---|
| **Artic C-Thru Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Dashboard to visualize the defined KPI's** | ICARE | WP5 | D5.2, D5.3 | Visualization | DC |
| **GEM Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Kafka connector** | NOVA ID, AIT, INTRA, UNPARALLEL | WP3 | D3.5, D3.6 | Connector | DC |
| **MAG CM Box Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **MAG Specht 600 Siemens Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Marposs gauge Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |

| | | | | | |
|---|---|---|---|---|---|
| **Pi Web Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Pi Web to Zeiss CMM Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Philips-MES connector** | PHILIPS | WP7 | D7.3, D7.4, D7.5 | Connector | DC |
| **Ptc Windchill connector** | PHILIPS | WP7 | D7.3, D7.4, D7.5 | Connector | DC |
| **Q-DAS Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **SAP connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **SAP MES Connector** | PHILIPS, JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **SAP MES Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Sharepoint connector** | PHILIPS | WP7 | D7.3, D7.4, D7.5 | Connector | DC |
| **Siemens MMT Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Zoller TMS Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Zoller Warehouse Connector** | JLR | WP7 | D7.6, D7.7, D7.8 | Connector | DC |
| **Wi-Care Sensors** | ICARE | WP3 | D3.5, D3.6 | Connector | DC |
| **Wi-care MQTT Sensor Data Collection** | ICARE | WP3 | D3.5, D3.6 | Connector | DC |
| **Wi-care Automatic Data Collection** | ICARE | WP4 | D4.1, D4.2 | Connector | DC |
| **Administration Shell connectors** | SENSAP | WP3 | D3.4 | Connector | MGMT |

*Table 5: Connectors Table (Data Collection for Use case instances)*

## A.3 Universal PdM KPI candidate list

| Group Level | ID / category | KPI Description |
|---|---|---|
| 1 | 1 | ECONOMIC KPIs (Managerial Level) |
| 2 | 1.1 | Total Cost of Maintenance Per Asset |
| 3 | 1.1.1 | Cost of Predictive (PdM) Maintenance (Yearly) |
| 3 | 1.1.2 | Cost of Preventive (PM) Maintenance (Yearly) |
| 3 | 1.1.3 | Cost of Corrective (CM) Maintenance (Yearly) |
| 3 | 1.1.4 | Cost of Unplanned-Other (UM) Maintenance (Yearly) |

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| 3 | 1.1.5 | Cost of Maintenance Training (Yearly) |
| 2 | 1.2 | TMC (Total Maintenance Cost) as a % of Asset Replacement Value (RAV) |
| 2 | 1.3 | Spare parts & Materials inventory value as a % of Asset Replace Value (RAV) |
| 2 | 1.4 | TMC (Total Maintenance Cost) of Asset per Asset Output (Yearly) |
| 3 | 1.4.1 | Cost of Predictive (PdM) of Asset per Asset Output (Yearly) |
| 3 | 1.4.2 | Cost of Preventive (PM) Maintenance of Asset per Asset Output (Yearly) |
| 3 | 1.4.3 | Cost of Corrective (CM) Maintenance of Asset per Asset Output (Yearly) |
| 3 | 1.4.4 | Cost of Unplanned-Other (UM) Maintenance of Asset per Asset Output (Yearly) |
| 2 | 1.5 | TMC (Total Maintenance Cost) of Asset per Total Manufacturing Cost |
| 3 | 1.5.1 | Cost of In House Maintenance Labor per TMC |
| 3 | 1.5.2 | Cost of Contractor Maintenance per TMC |
| 3 | 1.5.3 | Cost of Spare Parts per TMC |
| 2 | 1.6 | Useful Lifetime of Asset: Before / After |
| 3 | 1.6.1 | (RUL) Remaining Useful Lifetime of Asset (Before / After) |
| 3 | 1.6.2 | (TUL) Total Useful Lifetime of Asset since 1st installation (Before / After) |
| 2 | 1.7 | Optimal Stock Level |
| 3 | 1.7.1 | Spare parts stock turn ratio |
| 2 | 1.8 | Networked maintenance framework-Scalability to similar Plants |
| 2 | 1.9 | Cost Benefit Analysis |
| 3 | 1.9.1 | Cost Benefit Analysis of Predictive Maintenance Installation (Savings Yearly) |
| 3 | 1.9.2 | Cost Benefit Analysis of Predictive Maintenance Installation (Payback Period) |
| 1 | 2 | OPERATIONAL EFFICIENCY - ASSET UTILIZATION KPIs (Managerial Level) |
| 2 | 2.1 | RUL (Remaining Useful Life) |
| 2 | 2.2 | Repair Time (Prediction) |
| 2 | 2.3 | Asset Utilization (Asset Operating Time/Asset Maintenance Time) |
| 2 | 2.4 | Planned Downtime Versus Unplanned Downtime |
| 2 | 2.5 | Total Downtime (Planned+Unplanned) Versus Uptime |
| 3 | 2.5.1 | Unscheduled Downtime (Yearly) |
| 3 | 2.5.2 | Scheduled Downtime (Yearly) |
| 3 | 2.5.3 | Shutdown Overrun (Yearly) |
| 2 | 2.6 | Work Orders completed on time |
| 2 | 2.7 | Emergency & Overtime Operation vs Planned Operation (Yearly) |
| 2 | 2.8 | Percentage of maintenance work orders requiring rework (Yearly) |
| 2 | 2.9 | Availability (Asset operating time/Planned operating time) |
| 2 | 2.10 | OEE (Overall Equipment Effectiveness) |
| 1 | 3 | MAINTENANCE EFFICIENCY KPIs |
| 2 | 3.1 | per Station or Production Line |
| 3 | 3.1.1 | MTBF (Mean Time Between Failures) |
| 3 | 3.1.2 | MTTF (Mean Time To Failure) |
| 3 | 3.1.3 | MDT (Mean Down Time) |
| 3 | 3.1.4 | MTTR (Mean time to repair) |
| 3 | 3.1.5 | Failure Prediction because of Predictive (PdM) (after removed part inspection) |
| 3 | 3.1.6 | Failure Prediction because of Preventive (PM) (after removed part inspection) |
| 2 | 3.2 | Estimated Time Versus Actual Time Spent on a Planned Maintenance Day |
| 2 | 3.3 | Frequency of Total Failures (All types) |

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| 3 | 3.3.1 | Frequency of failure of 1st critical part (yearly) |
| 3 | 3.3.2 | Frequency of failure of 2nd critical part (yearly) |
| 2 | 3.4 | Frequency of Total Maintenance Events (yearly) |
| 3 | 3.4.1 | Frequency of Predictive (PdM) Maintenance Events (yearly) |
| 3 | 3.4.2 | Frequency of Preventive (PM)) Maintenance Events (yearly) |
| 3 | 3.4.3 | Frequency of Corrective (CM) Maintenance Events (yearly) |
| 3 | 3.4.4 | Frequency of Unplanned-Other (UM) Maintenance Events (yearly) |
| 2 | 3.5 | Maintenance Durations (per maintenance event-Average) |
| 3 | 3.5.1 | Duration of Predictive (PdM) Maintenance Events (Average) |
| 3 | 3.5.2 | Duration of Preventive (PM) Maintenance Events (Average) |
| 3 | 3.5.3 | Duration of Corrective (CM) Maintenance Events (Average) |
| 3 | 3.5.4 | Duration of Unplanned-Other (UM) Maintenance Events (Average) |
| 2 | 3.6 | Time Efficiency of maintenance event-Average) |
| 3 | 3.6.1 | Active Maintenance Time vs Run-Down+preparation+Delay+Rump up) |
| 3 | 3.6.2 | Delay of Spare Part Arrival (in unplanned (UM) and Corrective (CM) cases) |
| 3 | 3.6.3 | Delay of In House Workforce/Contractor Arrival in (UM) and (CM) cases |
| 3 | 3.6.4 | In House Workforce/Contractor Execution Response |
| 3 | 3.6.5 | In House Workforce/Contractor Execution Quality |
| 3 | 3.6.6 | Wrench time (% of time that a maint. technician works "tools-in-hand") |
| 2 | 3.7 | Identification of Primary root cause of faults |
| 3 | 3.7.1 | Based on Historical & Empirical Data |
| 3 | 3.7.2 | Based on Live Running Data |
| 3 | 3.7.3 | Based on Statistical & Correlation Data |
| 2 | 3.8 | Identification of Second root cause of faults |
| 3 | 3.8.1 | Based on Historical & Empirical Data |
| 3 | 3.8.2 | Based on Live Running Data |
| 3 | 3.8.3 | Based on Statistical & Correlation Data |