PROJECT FINAL REPORT

Grant Agreement number:	314762
Project acronym:	PRIME
Project title:	Plug and PRoduce Intelligent Multi Agent Environment based on Standard Technology
Funding Scheme:	FP7, Theme FoF.NMP.2012-3
Period covered:	01 November 2012 to 31 October 2015

Name, title and organisation of the scientific representative of the project's coordinator:

	Professor Svetan Ratchev, University of Nottingham
Tel:	+44 (0)115 951 4018
Fax:	+44 (0)115 951 3800
E-mail:	svetan.ratchev@nottingham.ac.uk

Project website address: www.prime-eu.com

Section 1: Executive Summary

The aim of the PRIME project is a paradigm shift from a conventional, resource-intensive, and largely human driven configuration and system integration process to plug and produce automated assembly systems with self-awareness and adaptation capabilities enabled by the development of an integrated PRIME methodology and toolbox.

The project particularly addresses the ability to integrate process units from different suppliers in a "plug and produce" assembly system without forcing the competitors to reveal their process and technology know-how. The PRIME project is one of the first to support smart process modules that encapsulate built-in manufacturing know-how that can not be accessed or copied by competitors.

Key Facts

PRIME
Plug and Produce Intelligent Multi Agent Environment based on standard Technology
Theme:
FoF.NMP.2012-3
Grant Agreement No:
314762
Start Date:
01 November 2012
Duration:
36 months
Project Coordinator:
The University of Nottingham

The PRIME approach utilises multi-agent systems, thereby addressing and developing a fundamental aspect for the successful and effective instantiation of plug and produce systems at SMEs which are different to operate, deploy and maintain in comparison with current logic based approaches. This gap between research and industry (the final consumers of the solution) is addressed by the PRIME project through the development of tools that enable a safe and easy deployment and instantiation of agent-based components and ensures that their potential is explored by key stakeholders. The outcomes of the project facilitate the development of configurable, self-aware, evolving and adaptive assembly systems that are easier to deploy and can react faster to fluctuations and disruptive events, thereby supporting an increase in productivity and yield.

Vision: PRIME aims to create new solutions for deployment by SMEs of highly adaptive, reconfigurable self-aware plug and produce assembly systems, which will use multi-agent control, dynamic knowledge sharing, integrated monitoring, and innovative human-machine interaction mechanisms. These next generation assembly systems equipped with PRIME technology will be able to proactively support rapid reconfiguration, adaptation, error-recovery, and operational performance improvement. This will lead to a dramatic cost and time reduction of deploying and maintaining complex assembly systems on demand and improve their effectiveness.

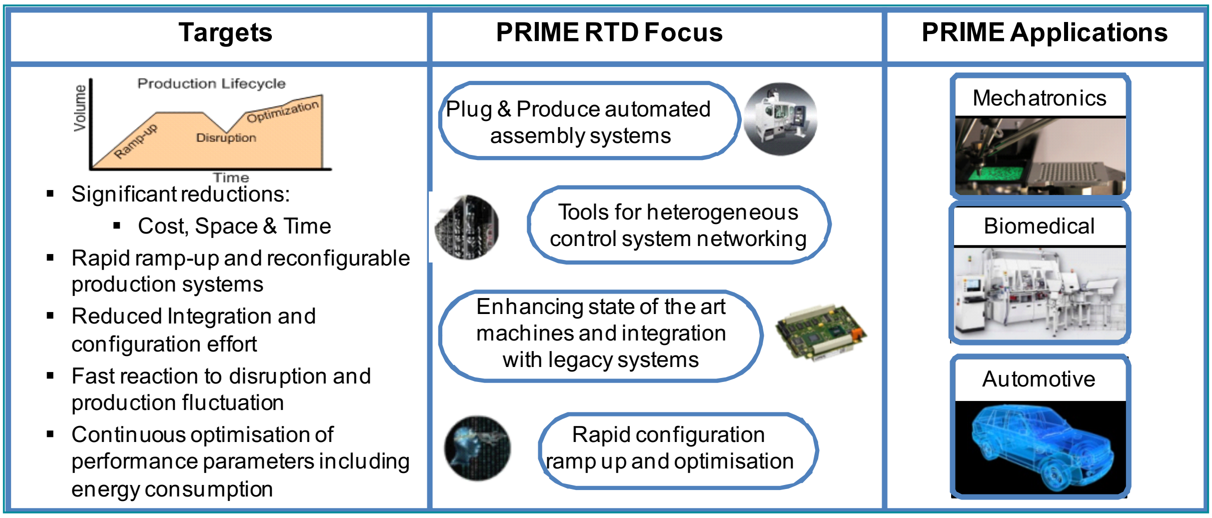

Figure 1. PRIME Vision Overview

Section 2: Summary Description

Introduction

PRIME is an EU FP7 project aimed at enabling the deployment of more efficient assembly systems by supporting both the planning and the evaluation of configuration options with respect to different baseline parameters, thereby ensuring that the right processes are employed at the right time. By enabling effective and continual system assessment, the project aims to deliver an improved efficiency of assembly lines in terms of increased levels of utilisation of modules by up to 30%. The reduction in reconfiguration times support the realisation of a highly responsive production environment that can be rapidly reconfigured for a new product or product variant. A traditional manufacturing system has a fixed output that, once reached, is difficult to alter irrespective of the marketplace. Figure 2 depicts how the PRIME approach allows assembly systems to closely match their capacity to changing market demand by adding or removing process modules throughout the product lifecycle.

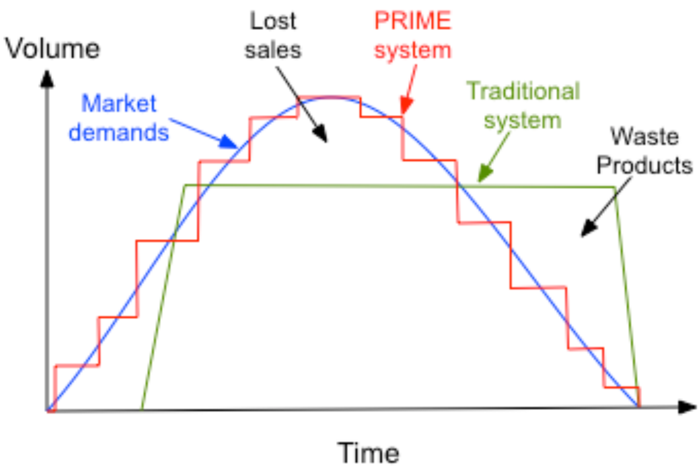

Figure 2. PRIME Project Benefits: Production volume (V) over time (t) comparison

The PRIME consortium brings together ten European partners from five countries

Partner	Country	Role
The University of Nottingham	UK	Project Coordinator, Higher Education Institute
Siemens	D	Industry, End User
SimPlan	D	SME, Technical Developer
TQC	UK	SME, End User
ASYRIL	CH	SME, End User
Zurich University of Applied Sciences	CH	Research Institute
Centre Suisse d'Electronique et de Microtechnique	CH	Research Institute
UNINOVA	PT	Academic
Technology Transfer System	I	SME, Technical Developer
INTROSYS	PT	SME, End User

This summary document explains the aims of the PRIME project in more detail, explores the science and technology developments, before concluding on the impact of PRIME through exploitable technology and industrial case studies.

Project Context

There is an increasing pressure on European SMEs to deliver high quality, often customised products using cost effective manufacturing processes and systems while competing in the global market. One of the key production processes in high labour cost areas such as Europe is assembly of final products in high value manufacturing industries. They all require systems that can: be installed quickly, achieve high volumes at shorter time intervals, perform with minimum interruptions and be reconfigured for new products with minimum cost. As a result, high value manufacturing is being transformed from using high capital-intensive assembly lines towards using dynamic assembly services on demand. This transformation is dictated by a number of factors: (1) increased demand for rapid ramp-up and downscale of production systems; (2) increased demand for assembly systems which can react to disruptive events and fluctuations during the production process; and (3) increased drive towards after sales service contracts for maintenance and upgrade of manufacturing systems.

Consequently, there is a need for a radically new approach towards plug and produce assembly systems that would allow extremely short set-up times combined with low cost of maintenance, system reconfiguration and capability upgrade. Within the context of the PRIME project, we define ‘plug and produce’ as a methodology for automatically managing the introduction/removal of assembly devices into/from an assembly system, as well as the introduction of products or product variants.

PRIME: Aims and Objectives

As noted in the introduction, the project aims to reduce the cost of installation and enhance the market responsiveness of assembly lines by reducing the reconfiguration times, cost and effort by up to 30% through functional realisation of the plug-and-produce paradigm. Similarly, time-to-recover from unpredictable events will be halved compared to the current-state-of-the-art using the knowledge a system has accumulated over its operational life. The development of a holistic, continuous learning system operation and optimisation environment is expected to raise the overall achievable performance and availability of assembly systems.

Historical data shows that on average 50% of the total time taken in assembly systems configuration is spent in functionally disconnecting and reconnecting individual modules. This encompasses the mechanical, electrical, service and software connections. In the case of assembly system reconfiguration, disconnecting and reconnecting requires more than 80% of the total time. Furthermore, the ramp-up effort contributes to around 65% of the cost of system installation. By introducing systems that can recognise and identify faults and learn the most appropriate solutions to bring a system up to and beyond full volume production, the ramp-up time can be significantly reduced. Indeed, estimations indicate that by reducing fault detection times by 50% the total ramp-up times can be reduced by up to 30%. PRIME is specifically focused on targeting three groups of SMEs: Component manufacturers, system integrators and end users. Overall this will result in significantly more efficient manufacturing systems, leading to European industry gaining a competitive advantage in the medium to long term.

In summary, initial projections from the industrial partners indicated that PRIME would be able deliver major quantifiable improvements in the medium to long term:

- Reduced ramp-up times by up to 50%
- Reduced time for system reconfiguration by 30%
- Increased system flexibility leading to increased level of product customisation by 40%
- System monitoring, optimisation and verification leading to reduction of rework by 30%
- Systems reaction to disruptive events (e.g. station and sensor failures) based on self-adaption and self-learning methods leading to 30% reduction of downtimes,

In addition to the impact that PRIME intends to deliver to the European manufacturing industry, the project is focused on producing a coherent set of tools, which interact together and provide a similar look and feel to the users. The tools will not only achieve the aims of PRIME, but do so by fitting into the existing production life cycle for production machines, thus minimising the need for process modification on the part of system integrators. The technical aims and objectives of the project, along with demonstrable impact based on results from the project demonstrators, are expanded in subsequent sections.

Section 3: Description of Main S&T Results

S&T Objectives

The aim of the PRIME project is a paradigm shift from a conventional, resource-intensive, and largely human driven configuration and system integration process to plug-and-produce automated assembly systems with self-awareness and adaptation capabilities enabled by the development of an integrated PRIME methodology and toolbox. The project aim is supported by the following key S&T objectives:

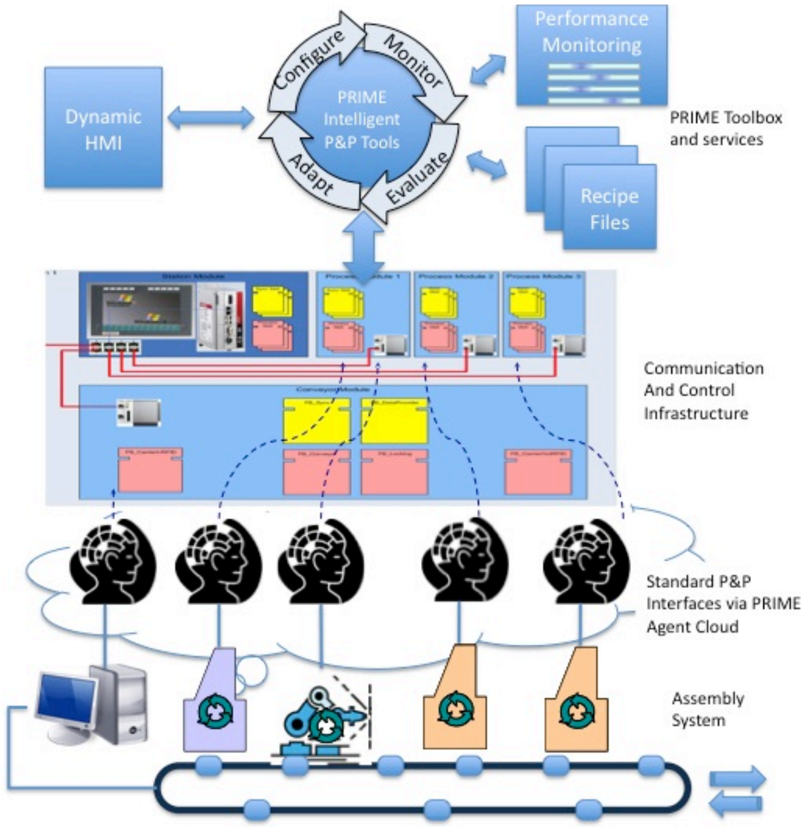

Figure 3. PRIME Concept

- Developing a vision and architecture for plug-and-produce variable volume multi-product assembly systems.
- Developing methods for rapid configuration, ramp-up and system optimisation and adaptation.
- Developing multi-agent control approach production environment for module integration including legacy equipment.
- Proposing a tool based on standard technology and language for integration and networking of heterogeneous control systems from different equipment suppliers inside a production line.
- Developing system behaviour model and real-time awareness methodology to support system evolution linked to process performance and product and volume variability.
- Integrating and enhancing state-of-the-art machines and production systems with plug-and-produce capabilities and interfaces for seamless integration
- Supporting the system-to-service transformation in assembly by automating the deployment of manufacturing services into the line.

As has been widely reported, there are a number of specific barriers that have been identified preventing the adoption of the latest manufacturing techniques and systems by SMEs including: high cost of ownership, lack of critical mass and skills and lack of appropriate standard manufacturing system components allowing cost effective flexibility and reconfigurability.

Within the SME manufacturing sector there is an increasing need to dynamically reconfigure manufacturing platforms to produce a wider range of products. In extreme cases of product diversification, individual items require unique customisation. In addition to this, SMEs often have complex manufacturing setups, and operate a range of devices from multiple vendors. This can be as a result of individually pricing components within a factory in order to minimise costs, or as a result of requiring bespoke devices for specialist manufacture. This methodology not only makes designing complete manufacturing systems complex, but also requires a large range of technical skills in order to combine multiple platforms into compound systems. In addition, should controllers fail or require upgrading, SMEs can find themselves locked into a specific controller manufacturer or face re-writing the control software for an entire component. The complexity of the resulting solutions, and the critical time constraints involved within the manufacturing sector, mean that the resulting solutions can be prone to system-wide failure due to a single malfunction, and be difficult to monitor and control from a management perspective.

PRIME introduces two key technologies to make the design, maintenance and management of SME manufacturing systems cheaper, faster and more robust: multi-agent control and information-rich development tools. The PRIME concept (Figure 3) is detailed further below.

PRIME Concept

PRIME proposes a user centric approach providing a toolbox with the following guiding design principles:

- Quick Instantiation and Deployment of Agents in different industrial controllers: it is fundamental to ensure that the multi-agent approach can be instantiated in devices from different manufacturers. This enables the end user of the system to develop, build and extend its own system using these heterogeneous hardware components harmonised at process agent level where a standard language, open and manufacturer agnostic can be used. The PRIME toolbox should be open and generic enough to accommodate new data from new manufacturers and automatically ensure that new process unit agents can be instantiated and deployed in those devices.
- Managing and integrating process oriented knowledge for configuration and execution purposes as different users and stakeholders would require different views and interactions with the system. The PRIME toolbox will allow multi-view approach so that every stakeholder can manage and benefit from the system according to their specific needs.
- Supporting the life cycle of Plug and Produce Mechatronic Agents (Agent + Controller + Equipment) during Deployment and Runtime: Periodically the assembly systems will need to reconfigure to meet a new business opportunities and product and process requirements. PRIME renders these changes seamless by providing the adequate interface for creating and deploying new Process Unit Mechatronic Agents (MA) or even modify or remove them from the system. Each part composing the MA can be further reused to generate or host new functionality.

- Managing, Monitoring and Controlling the Plug and Produce Mechatronic Agent Environment created with the PRIME Tool Box, allowing the deployment of an Agent in several devices. This implies that the devices are ready to receive a PRIME MA or that some structures have been created to ensure interoperability. PRIME will provide tools that help to manage these infrastructural aspects of the platform to support testing devices beyond the agent approach to make sure that all the deployment conditions are gathered.
- Assessing the performance of the system: providing a holistic view on the system the PRIME toolbox will incorporate in an open way the introduction of several performance metrics that can used to evaluate several aspects of the system behaviour.
- Assessing the most effective solution given the existing hardware according to performance or cost metrics: one of the fundamental consequences of the previous point is that performance and cost metrics enable the user to take informed decisions on the best MA instantiation given the design objectives and cost constraints.

Industrial Focus

The industrial focus of the project is realised through three demonstrator platforms aimed at strategic EU sectors: (1) Mechatronic assembly (Asyril); (2) Assembly of Automotive Parts (TQC); (3) Automotive robotic assembly cells (Introsys). The table below breaks down the pilot cases presenting an overview of their relevance and challenges.

	Mechatronic Assembly	Assembly of Automotive Parts	Automotive Robotic Assembly Cell
Relevance	High precision assembly operations Increasing importance of system reliability as production volumes increase	Accelerated integration of product variants Rapid growth world-wide for model introductions	Car manufacture represents one of the key sectors in Europe. Competitive supply chains and a complex supplier base.
Challenges	Components designed in isolation resulting in higher complexity range of solutions that demand larger technical skill base.	Customised assembly requires fast system reconfiguration. Realisation of adaptation technologies to enable rapid product change and ramp-up.	Solutions provided through multiple vendor systems which result in increased costs and bespoke devices.
Demonstration	Asyril Demonstrate communication infrastructure of underlying multi-agent system	TQC Demonstrate complete Plug and Produce cycle to assembly product and variants	Introsys Demonstrate monitoring and data analysis functionality

Summary of Results

Following the PRIME Concept description above, this subsection provides an overview of the main scientific and technological results, grouped by subsystem. A high level component overview of PRIME is detailed in Figure 4 for reference. Further detail is covered by the PRIME Architecture description.

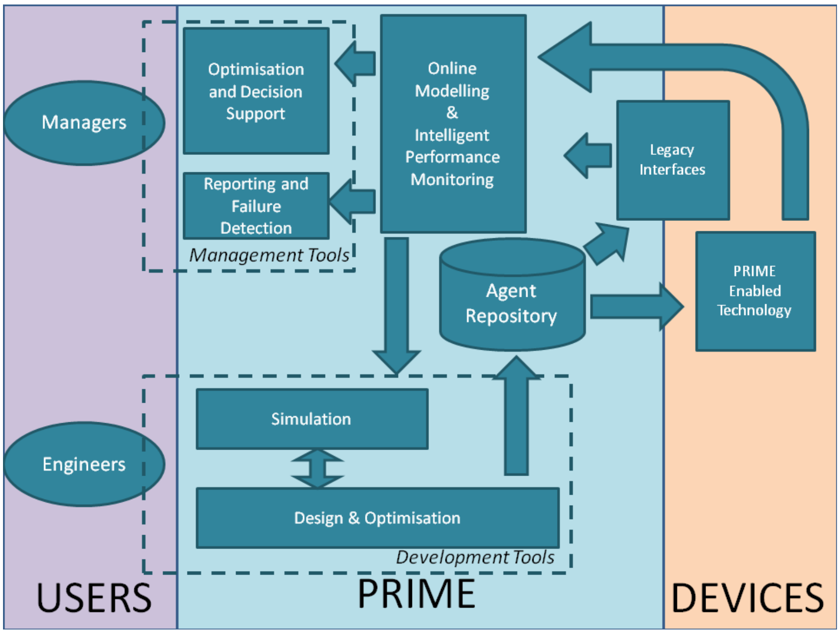

Figure 4. A High Level Component Overview of PRIME

PRIME Architecture

The PRIME Architecture and component description is detailed below for reference. The aim of the PRIME architecture is to define and formalise a common vision of PRIME in terms of architecture requirements and guidelines that act as a common reference model for all the S&T developments. This has been realised in close collaboration with all project partners and with a clear focus on the industrial requirements. The architecture caters for all PRIME use cases, specifies how components interact using the communication infrastructure and is structured according to distinctions identified in implementing 'Plug and Produce'.

System Overview

Considering the wider requirements of plug and produce systems, and material produced both during and after the Requirements Workshops, the functionality of PRIME can be stated to be:

- PRIME implements plug and produce
- PRIME implements integration of existing legacy systems
- PRIME implements performance monitoring, data analysis and optimisation

In order to implement this functionality, the following technologies have been developed and implemented:

- PRIME is a multi-agent system-based framework for production systems
- PRIME implements awareness and self-awareness
- PRIME implements adaptation and self-adaptation

Within PRIME self-awareness and self-adaptation are instantiated at three levels:

- Data
- Production device
- Product

Decomposition View of PRIME

PRIME is designed as a set of software modules (units of implementation), of which there are four (Figure 5).

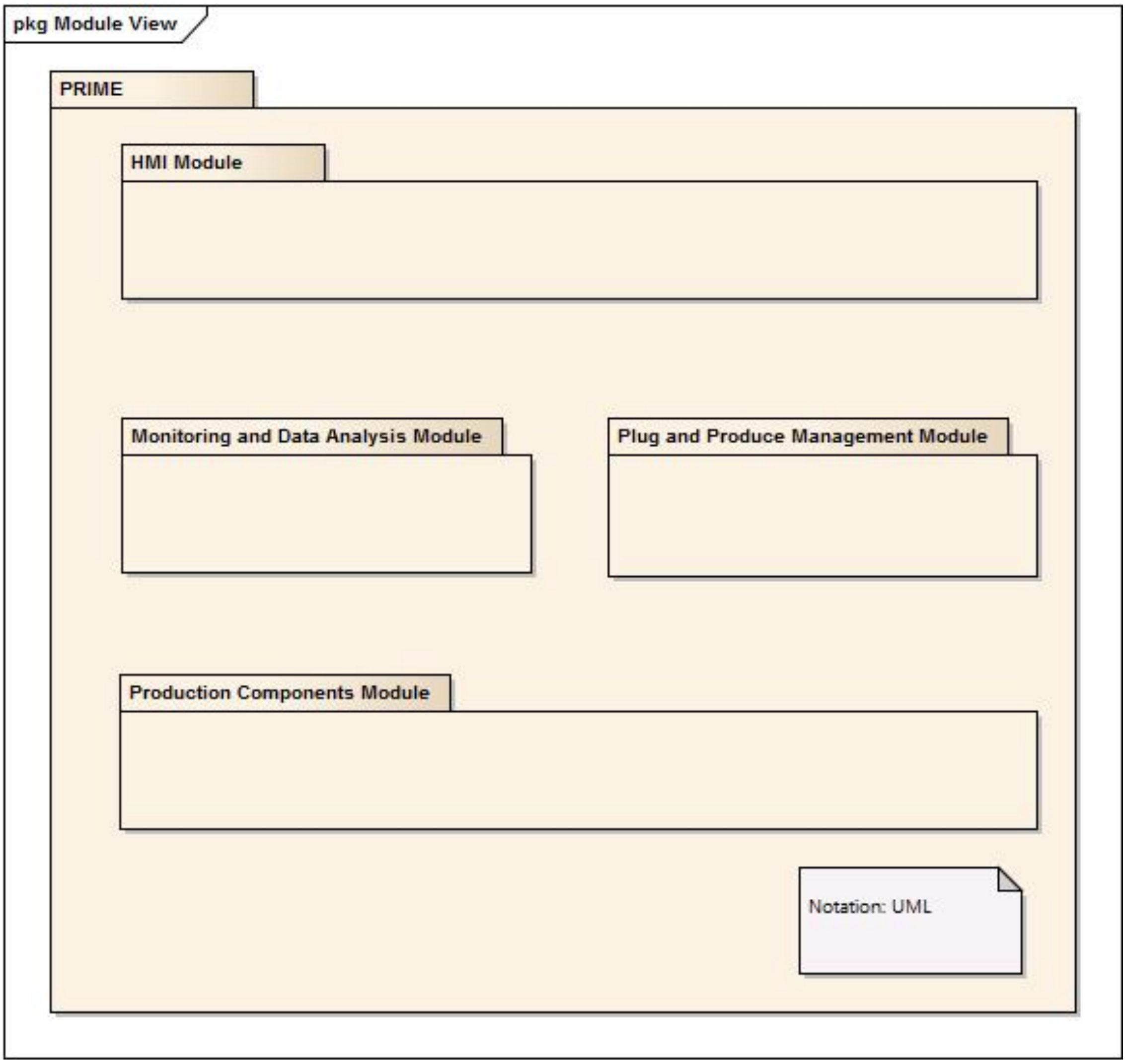

Figure 5. Decomposition view for the PRIME system

Production Components Module - This module is a representation of the production components of a given production system. The agents in this module are Production Component Agents, Components Agents (CAs) and Deployment Agents (DAs). Any individual Component Agent is associated to one production component. A Component Agent is the interface between its associated production component and the multi-agent system.

Monitoring and Data Analysis Module - This module monitors and analyses data from production components. The agents in this module are the Local Monitoring and Data Analysis Agents (LMDAs). They collect relevant I/O from their corresponding production devices and perform pre-processing operation on these I/O.

Plug and Produce Management Module - This module manages the plug and produce operations of a production component or a product. The agents in this module are:

1. The PRIME System Agent (PSA)
2. Product Agent (PA)
3. Deployment Agent (DA), which deploys the corresponding PA.
4. Production Management Agents (PMAs)
5. Capability Management Agents (CMAs)

HMI Module - This module collects and displays relevant information regarding plug and produce operation or monitoring tasks. This HMI is independent of the supervision HMI that operators use for supervising and controlling a process. Its associated agent is the HMI Agent (HMIA).

Specific interactions between these modules implement the underlying technology that delivers a desired functionality. In the following sections, for each item of functionality; the software modules are described including how this interaction implements the underlying technology that delivers the associated functionality.

Plug and Produce, and Integration of Legacy Systems

The plug and produce and the integration of legacy systems functionality is delivered by implementing both device and product level self-awareness/adaptation. The modules that implement these technologies are: HMI Module, Plug and Produce Management Module, and Production Components Module.

Figure 6 is the component-and-connector view that implements both plug and produce, and integration of legacy systems. This illustration shows elements that have runtime presence such as the HMI, agents, databases, and the control system. Additionally, this presentation includes the pathways of interaction, such as communication links and protocols, and access to storage components.

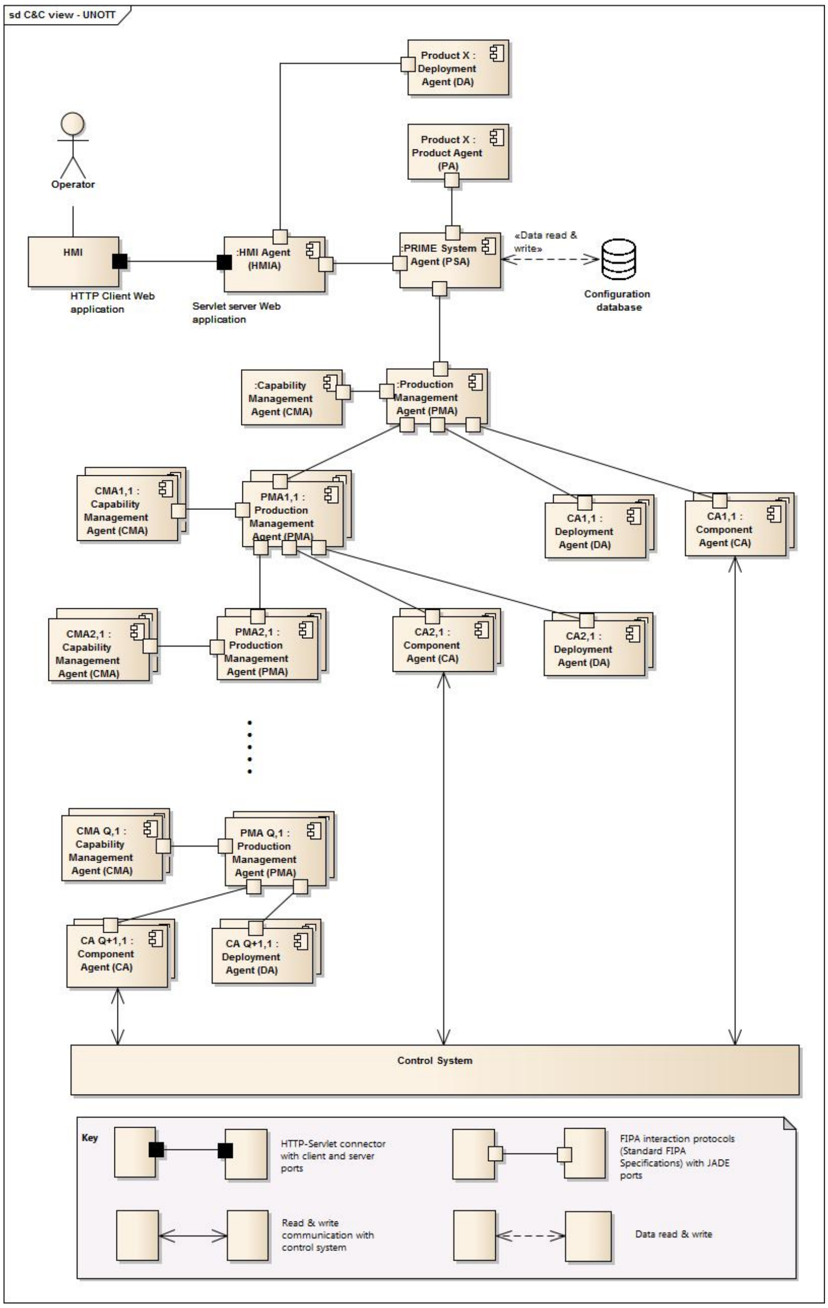

Figure 6. Client-server and peer-to-peer views for plug and produce, and integration of legacy systems

Performance Monitoring, Data Analysis and Optimisation

This functionality is delivered by implementing both data level self-awareness/adaptation. The modules that implement these technologies are: HMI Module, Monitoring and Data Analysis Module, and Production Components Module.

Figure 7 is the component-and-connector view that implements the monitoring, data analysis, and optimisation of production systems. Agents were selected for collecting I/O because a multi-agent system framework such as Jade provides the functionality for creating, destroying, and configuring components. With respect to the data stream processing framework, RxJava is utilised due to the fact that it is the most light-weight solution that satisfies PRIME's requirements. For data storage, Apache Cassandra meets with the needs of a production environment that handles large amounts of data across many production lines and, potentially, many servers.

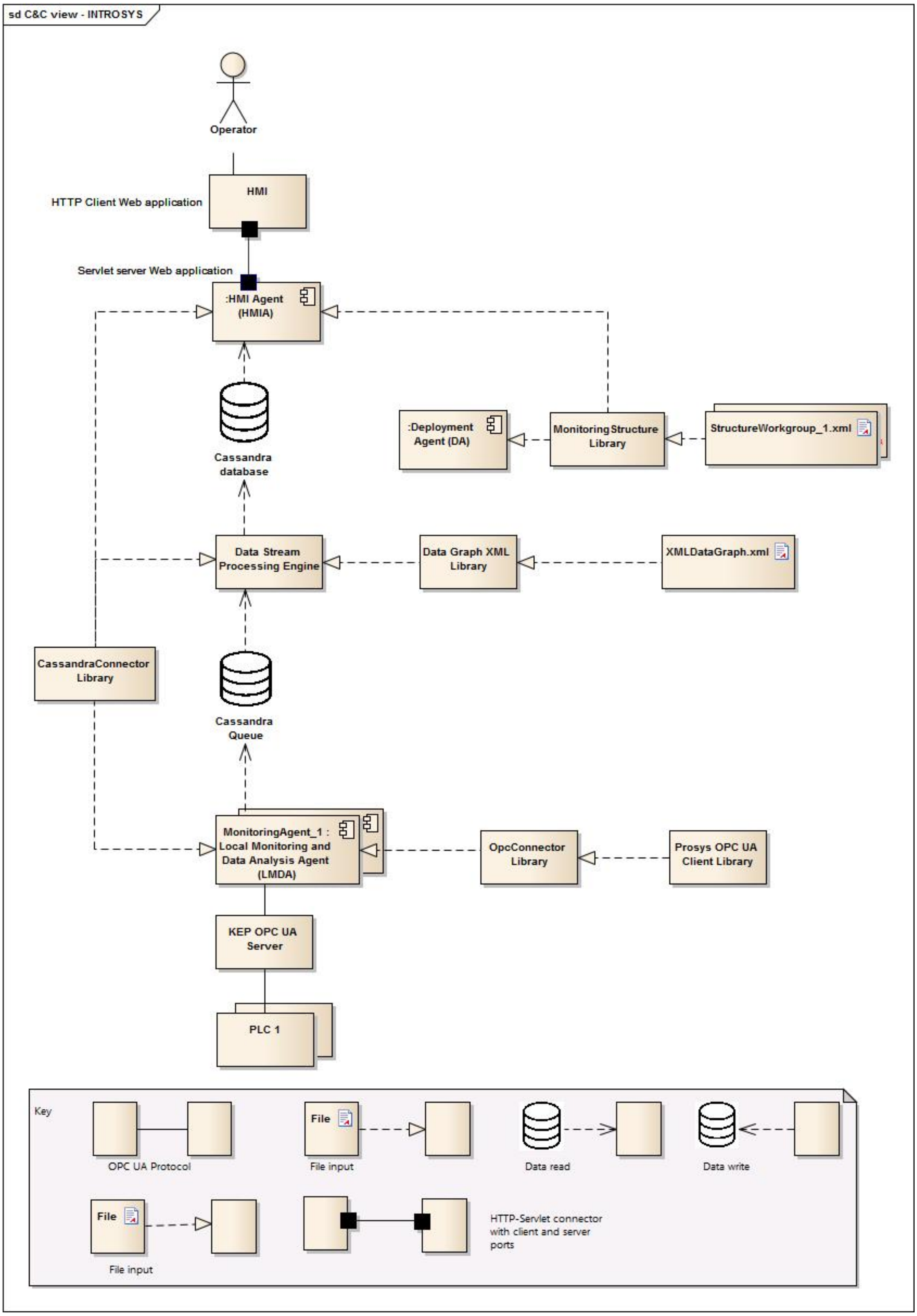

Figure 7. Client-server, peer-to-peer, and pipe-and-filter for performance monitoring, data analysis, and optimisation

PRIME as a Process: Proving PRIME Works

PRIME is not simply a collection of functional components. It is a coherent toolbox solution that allows disruptions to production to be corrected and efficiently through integration into the standard production life-cycle. Three industrial case studies were explored throughout the lifetime of the PRIME project with SME end users. The demonstrators and associated results are detailed below. Each demonstrator represents an increasingly complex instantiation of the PRIME architecture. Videos of the three demonstrators can be viewed from the PRIME website. N.B. The impact of each demonstrator is presented in Section 4: Potential Impact.

Industrial Case Studies

Demonstrator 1 - Asyril

Asyril is focused on proposing flexible solutions to feed and manipulate small parts. It develops and sells components such as robots and feeders as well as modular machines based on these components and supports different configurations (e.g. number of cameras and feeders).

To cover the feeding and manipulation needs for parts ranging from ~0.5 mm to 20 mm, series of components have been developed, in particular robots with varied workspaces and feeders with different size of picking surface. These components can then be combined and delivered with a vision system, integrated as a palletizing module or as an autonomous palletizing cell. All these systems use common controllers and graphical user interfaces (GUI) that have to be configured depending on the number, functionality and characteristics of the "basic" components (robots, feeders, cameras) as well as their interactions (e.g. which camera corresponds to which feeder). Communication ports also have to be specified and configured depending on the connected component.

In the 'pre-PRIME' scenario, the configuration is completed manually based on written procedures and it is a highly time-consuming task. Therefore the expected impact of PRIME concerns:

- The reduction of the configuration time
- The reduction of the risk of errors during the configuration of the machine
- The simplification of the user interaction to a non-expert person

Asyril Demonstrator Structure

For the PRIME demonstrator, Asyril built a machine based on a "Power Delta" that can pick parts (products) from one or two feeders (Asycube Forte) depending on the application. Each feeder is combined with a camera and together they form two identical subsystems. Each component is then directly connected to a PC.

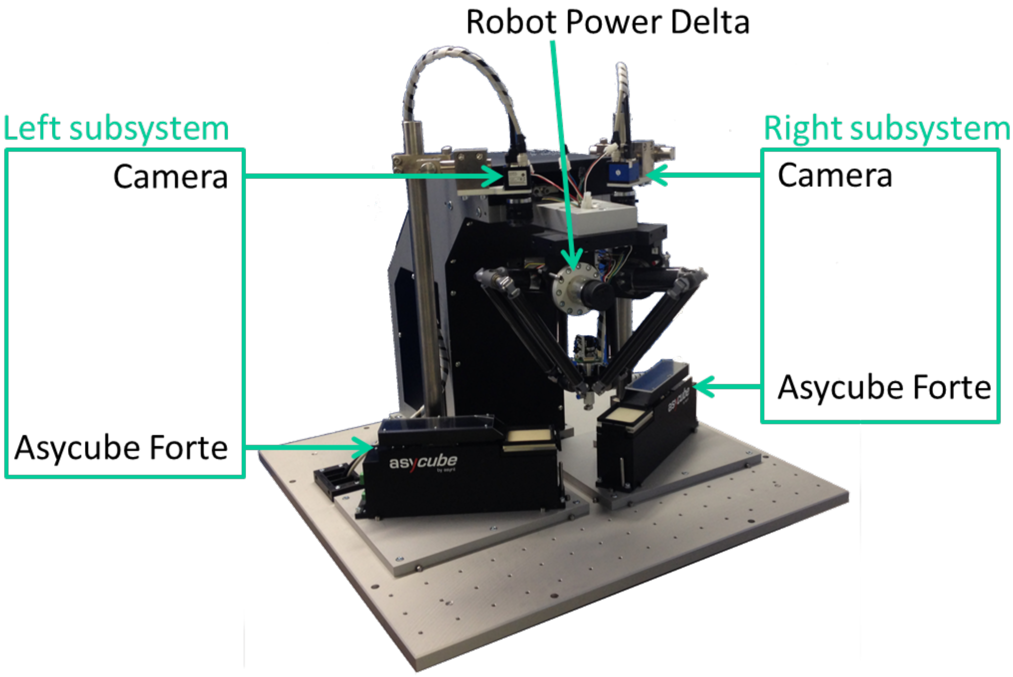

Figure 8. PRIME Demonstrator 1

The elements of PRIME to be demonstrated on Demonstrator 1 do not require a specific product. The purpose of Demonstrator 1 is to illustrate and showcase a working communication infrastructure. The components and structure used by Asyril allow a product-independent set-up of the demonstrator. Product specific adaption will be conducted software-wise mainly and can be loaded as a recipe. Only components which interact with the product directly will need to be adapted physically (i.e. gripper and eventually the pallet) once a product is chosen. Therefore the choice of the product itself is considered non-critical. Once the configuration / topology is built or updated the user selects the corresponding recipe or adjusts it (part or all of the following adaption tasks: calibration, frame and position learning, vision model teaching, vibration optimization) before commencing production.

The PRIME demonstrator 1 was designed to use legacy controllers that do not directly provide a PRIME agent. A multi-layer approach (Figure 9) separated the system into different logical areas and achieved communication between the agent society and Asryil's hardware. While the PRIME architecture has already been described elements specific to demonstrator 1 are covered below. The deployment agent was responsible for generating PRIME component agents. It periodically communicates with the detection library to receive the list of devices and outputs its results to the PRIME GUI. This interface is an intermediate development of the final PRIME GUI which was not part of Demonstrator 1. It provides the main functionalities but not the expected flexibility and extended behavior of the final PRIME GUI. Using this interface the user can place a newly detected component within a group. In terms of demonstrator 1 this functionality allows users to group together a camera and a feeder, thus enabling them to define which camera will be associated with which feeder. Once the user has verified these operations the PRIME component agent can be created using the communication library whose name was received from the deployment agent via the detection library. This agent handles all PRIME tasks for a given device. It is the PRIME representation of a piece of hardware. The complete description of the PRIME system, containing the connected devices and their characteristics, is covered by the PRIME topology.

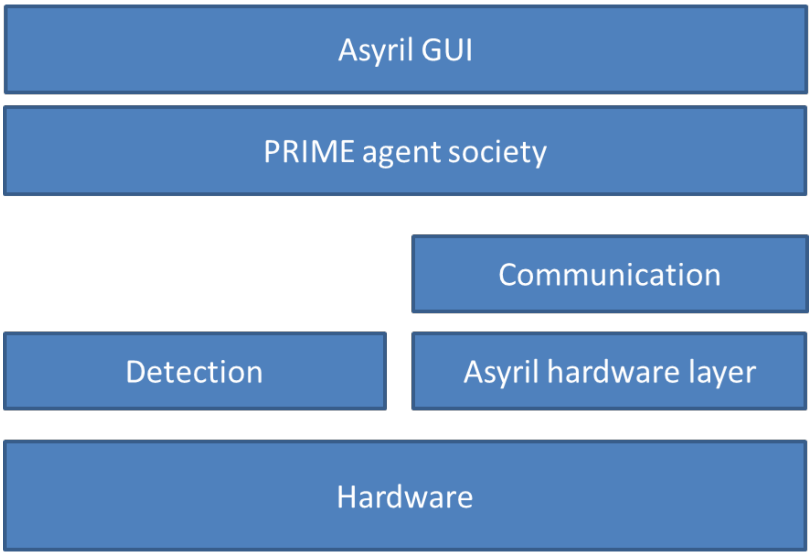

Figure 9. Demonstrator 1 layered architecture

Demonstrator 1 Achievements

The first demonstrator presented at the Mid-Term Review (May 2014) highlights the challenge faced by small lot-size production with frequent product changeover and reconfiguration. It demonstrates the plug and produce agent based run time environment used to reconfigure equipment between product specifications.

This demonstrator corresponds to the first implementation of the PRIME multi-agent system on real equipment in which the following tasks were achieved:

- Detection of 'plugged in' and 'plugged out of' different hardware components (robot, feeders, cameras)
- Communication between PRIME and the control logic
- Reading values from components through the agent system
- Recognition of the topology (number and type of connected components)
- Notifying the control logic and the HMI of any modification in the configuration

Demonstrator 2 - TQC

TQC provides special purpose, innovative turnkey solutions for a broad spectrum of industries. The systems can be full production lines or simple fixtures. Some examples of systems supplied are automated assembly, leak testing machines, laser marking and welding machines, test equipment and robotic handling solutions. Typically, 50% of the lead-time required to deliver a typical manufacturing system is due to the specific integration challenges associated with procured equipment.

The expected impact of PRIME for TQC comprises:

- Analysis of the Guidelines and support for the generation of the necessary control structures that could be used on several projects with a view to reducing the lead-time to delivery by at least 35%.

- Efficiency gains in modification and reconfiguration of an existing workstation.
- Easy substitution of production components
- Configuration gains in expansion of the system when using shared resources or components.
- Support for reconfiguration due to changes in product variation.
- Support for data collection and integration with Management Information Systems (MIS).
- Dynamic machine performance with corrective actions.

The purpose of demonstrator 2 is to implement and evaluate the PRIME software tools that support plug and produce technology within an assembly system. PRIME tools support static and dynamic (re)configuration of the production components and, as a consequence, the assembly sequence. These features facilitate the assembly of product variants without necessarily stopping the production line.

Demonstrator 2 also exhibits the PRIME 'Smart' HMI that allows operators to:

- select product variants for assembly,
- select or deselect optional operations (e.g. quality tests),
- gain assistance on the services required and available to assemble the chosen product variant,
- configure assembly by providing parameter values,
- run and supervise the execution of the assembly system, and
- monitor the agent interactions during runtime.

TQC Demonstrator Structure

Demonstrator 2 comprises a modular assembly system (Modutec) from Feintool and accommodates up to eight stations that can work together in a free sequence in relatively little space. A transportation system is installed to serve all stations. Each station in the Modutec unit can be physically removed and replaced if required; and each has its own controller unit housed directly beneath the station work top.

Figure 10. PRIME Demonstrator 2

The stations in demonstrator 2 are occupied by two identical KUKA robots, a tool rack (from Schunk), and an inspection unit. Two stations, each adjacent to one robot, are used as work areas for the assembly process. The tool rack sits in a station between the two robots so that both can access any of its six end-effectors. The relative position of the tools in the rack is not predetermined and frequently changes during the assembly. Each robot can complete a partial or complete assembly of the product as designated by the operator. The product (hinge, for exploded view see Figure 11) is presented to each station on a bespoke pallet, which is transported on a shuttle. The robots and inspection units are able to pick up the pallet and place it in their work area. The shuttle is then free to transport another pallet if required. Assembly of the hinge takes place on the pallet.

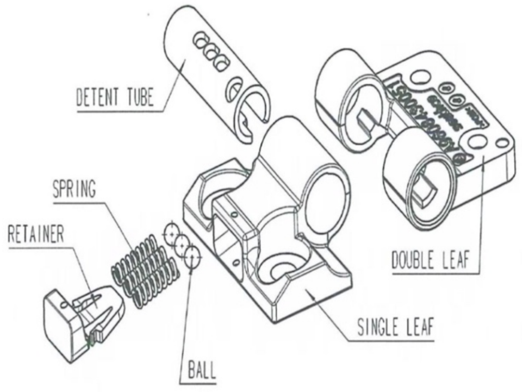

Figure 11. Exploded view of the product

In the case of Demonstrator 2, PRIME was applied in order to provide plug and produce capabilities to resources and to reconfigure the whole production system. The resources such as robots, effectors and testing stations are treated as encapsulated modules. In other words, PRIME configures those modules but does not control them in real-time. Therefore, each module is represented by a software entity called a Component Agent. A network of these agents is called a multi-agent system which is used to interface with the control system and to reason about reconfiguration operations.

The software architecture is composed of agent modules. This separates the agents in logical classes and assures clear interfaces between both, different agent types and the control and multi-agent system. Agents for reasoning (skill management agent, production management agent and product agent) are located on a desktop computer. This implementation was chosen as the desktop computer's RAM memory has enough capacity to host these agents. However, these agents could be hosted by the main PLC provided that its memory is expanded. Component agents, which are responsible for accessing the production components, are physically situated on the legacy controllers. Figure 12 illustrates the reconfiguration procedure in terms of agent behaviour and interaction.

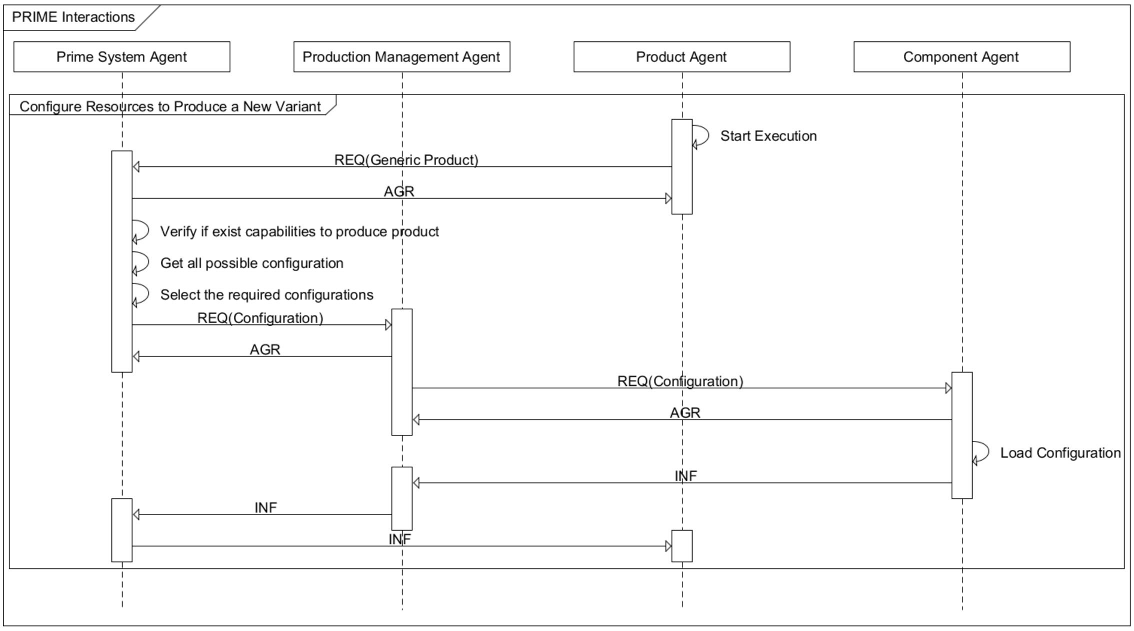

Figure 12. Agents behaviour and interactions during reconfiguration

Demonstrator 2 Achievements

Demonstrator 2 completed the second implementation of the PRIME system on an industrial assembly platform and is used to validate:

- Plug and produce capabilities with standard technology
- A multi-agent architecture to manage the reconfiguration of:
    - A new production layout
    - A product changeover

Two production scenarios were set up to demonstrate and evaluate PRIME on demonstrator 2. These comprised plugging in and plugging out a production resource. Both scenarios were tested in two environments. The first included a situation in which the assembly system is not assembling a product whilst in the second the system is in operation. In both cases, PRIME reconfigures the production system successfully between product batches. After reconfiguration, the PLC code manages the new situation by executing the just configured control logic.

The following objectives were achieved during the implementation of PRIME:

- Management of any plug and produce activity in the system.
- Self-awareness/adaptation of production modules.
- Efficient interfacing between PRIME (multi-agent system) and production resources.
- Matching between product requirements and production skills for the reconfiguration.
- Reconfiguration of the production line without specialised process control knowledge.
- Multi-agent assisted decision making for most suitable configuration.
- A module supplier does not need to disclose proprietary software/hardware specifications to a PRIME user, they describe their modules by means of a blue print file.

It is noted that the the modules used in demonstrator 2 are PRIME-enabled as opposed to legacy devices. This means that the PRIME component agent is an intrinsic part of each production module on an assembly station. As such, the PRIME project considerations pertaining to legacy devices were not considered in this analysis since PRIME was applied to legacy devices in Demonstrator 1.

Demonstrator 3 - Introsys

Introsys is both a reference Controls House for the European Manufacturing Industry and second tier supplier which provides integrated solutions of control systems for the automotive sector. These solutions include, hardware planning and design, the development of systems control with industrial PLCs as well as robot programming, and robot and PLC process simulation.

Demonstrator 3 is intended to illustrate a self-aware system capable of providing decision support to work around malfunctions and sudden requirement changes applied to the manufacture of complex products within the automotive sector. In order to validate and assess the proposed methodology, two robotized manufacturing cells located at Introsys were used. The cells include a loading station used to load car components, a robot manipulator and a welding station. The cells are identical in terms of functionalities, i.e. once a part is loaded the robots perform the same actions on it according to the sequence: pick-weld-place. However, they have been designed and developed using two different proprietary standards, from two distinct car manufacturers. With the PRIME demonstrator Introsys intends to show that monitoring and maintenance tasks/tools could be made more efficient and accessible in order to optimize the performance of a production system.

Introsys Demonstrator Structure

Demonstrator 3 comprises two industrial cells, each built to different standards that replicate cells from competing automotive companies. Figure 13 presents a simplified layout of the demonstrator 3, which shows the two industrial cells. Each cell has a different robot and a PLC, supplied from different manufacturers. Each PLC is responsible for the control of the entire process in its cell.

The two cells perform exactly the same tasks, producing exactly the same product. Each cell comprises:

- One robot
- One robot gripper
- One welding gun
- Three clamps
- One pin
- PLC
- Safety hardware (Scanner, Door, Light Barrier)
- Sensors

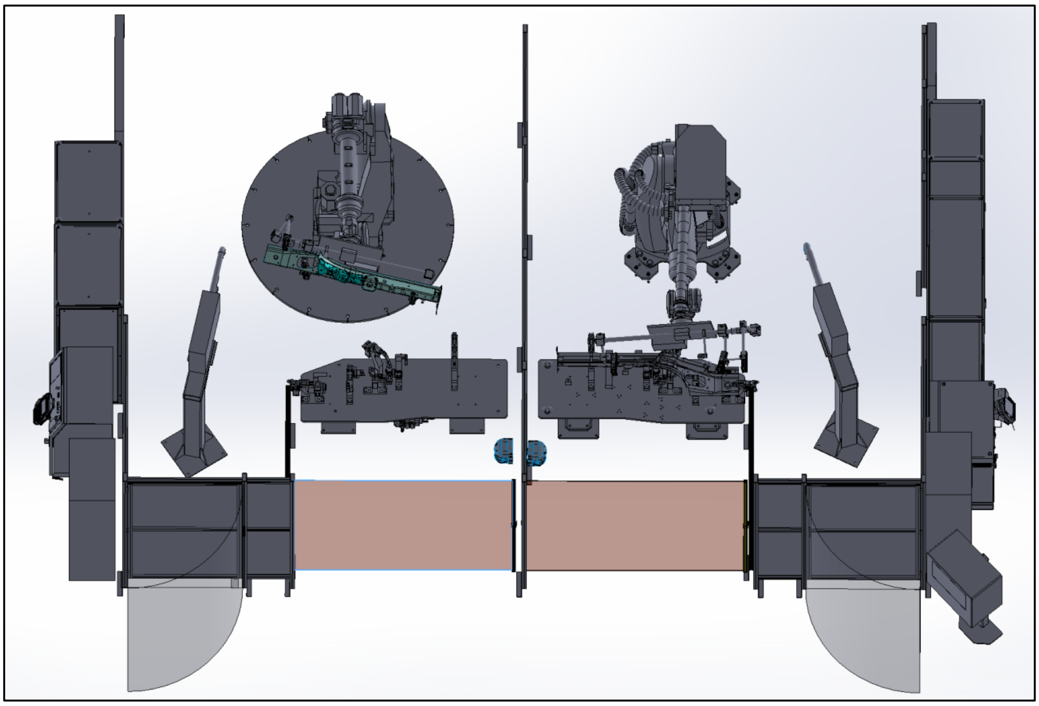

Figure 13. Demonstrator 3 Layout

Although the two cells produce exactly the same product, it is easy to detect differences because of the hardware used in each cell and the differing standards employed. Differences between the cells cover:

- Standards
- Equipment
- Programming

However, the two cells have many characteristics in common including:

- Structure of the robot (Robot with equal grippers)
- Station (Station with three clamps and one pin)
- Safety hardware (one door, one light barrier and one laser scanner)
- Produce the same product

As described previously, each cell has its own independent PLC with responsibility for the control of the process within its cell.

Demonstrator 3 was designed to be easily deployed and usable. Several highly cohesive modules have been developed with well-defined interfaces that achieve a separation of concerns. In this way, it is possible for the operators and system integrators to integrate and deploy new components and entire new systems using this architecture. Although a significant number of software modules have to be developed, each module is simple to deploy. Furthermore, for deploying a PRIME monitoring environment only a few modules need to be edited and the majority do not require any programming effort. Figure 14 presents an overview of the entire demonstrator 3 architecture and all associated modules.

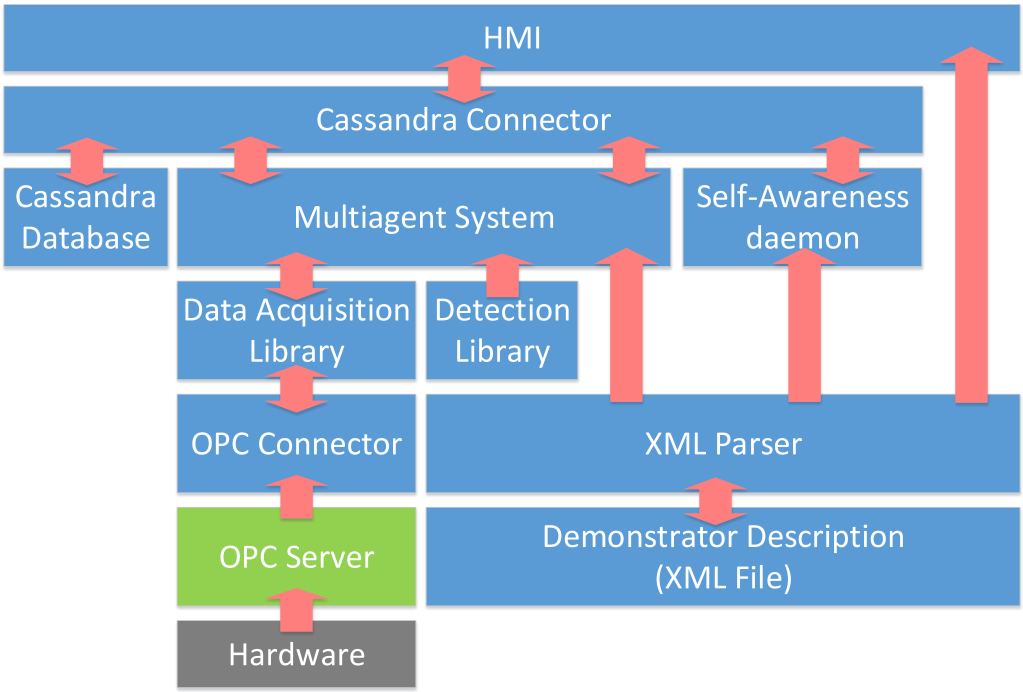

Figure 14. Demonstrator 3 Architecture

The architecture overview shows boxes in three different colours. The blue boxes represent all the PRIME modules developed in order to perform monitoring and self-awareness/adapatation. The green one represents a module constituted for software that already exists but configured in order to retrieve the correct values from the system and the grey box represents the hardware already in existence and running.

Demonstrator 3 Achievements

The purpose of demonstrator 3 is to introduce the ability for monitoring and to perform self-awareness in a PRIME enabled environment. Hence, the main objective of this demonstrator is to show how to instantiate the PRIME architecture and auxiliary tools in order to perform monitoring in a heterogeneous production line, in this case comprising two different cells, composed from different standards and hardware.

In summary, to demonstrate all the functionality, the demonstrator needs to be able to:

- Instantiate the PRIME multi-agent framework.
- Interface the multi-agent framework with the hardware.
- Instantiate the self-awareness module.
- Instantiate the HMI with its capability to show the entire production system.
- Interface the multi-agent architecture with the self-awareness module and the HMI.

The developed modules, working together, must be able to:

- Extract raw data from the PLCs.
- Pre-process raw data and generate new knowledge based on the extracted raw data.
- Show the current state of the system to the operator.
- Show issues detected on the system, by the self-awareness module.
- Compute trends, which can result in alerts and advices to the operator.

- Consult historical data about execution times, performance, issues, etc. Scenarios have been set up to demonstrate and test the PRIME infrastructure and capabilities for this purpose.

The main focus of the demonstrator is to show the ability to perform monitoring, knowledge extraction and self-awareness. So, the demonstrator will have an HMI showing the current state, performance evolution and issues or problems with the hardware of all monitored resources.

As such demonstrator 3 comprises three distinct parts:

1. Standard Demonstrator (Standard Technology): This part has all the physical resources that constitute the two cells, such as robots, clamps, safety components and pins; all the controllers necessary to control the robots and the process (PLCs); the operators; parts and the wired network that connect all the components and controllers.
2. Knowledge Extraction / Processing: Most of the PRIME environment components reside in this layer. The role of this layer is to extract data from the PLCs, use the OPC-UA protocol, store the information, process it and generate new knowledge that is also stored.
3. Web based HMI (Multiple Instantiations): This layer constitutes the higher level layer on the entire demonstrator, and consists of the HMI itself. It holds the results of the PRIME environment and all data retrieved and generated from the demonstrator can be displayed on the web-based PRIME HMI. For instance, it is possible for the operator or production manager to consult and analyse the performance of the cells and avoid existing and possible issues detected by the self-awareness network.

Demonstrator 3 is the third and final implementation and instantiation of the PRIME environment. Regarding this instantiation, several achievements are noted:

- A generic OPC Connector has been developed in order to allow data extraction from the PLCs, using standard technology.
- Development of the monitoring agents, capable to offer data acquisition and pre-processing for the PRIME multi-agent environment.
- An XML structure has been proposed to describe a production environment. This XML structure is used by the other modules to understand the topology of the system and other relevant information about the system.
- A database has been developed to work as a data buffer (queue) and historical data storage. The database has been implemented using a Cassandra database (NoSQL database).
- A Detection Library, based on the XML file with the topology of the system, has been completed, to deploy automatically the agents responsible to abstract the system.
- A Communication Library which instantiates the generic OPC Connector with the values to collect has been created and used by the monitoring agents.
- A generic XML parser has been developed. This generic library is used by the agents, HMI and Self-Awareness daemon to extract the topology of the system.
- The Self-Awareness daemon has been developed and integrated. This daemon constantly analyses the extracted data and understand possible problems occurring in

the present and / or problems that can occur in the future, informing the operator and / or production manager about possible maintenance before issues arise, damage hardware and result in system stoppages.

- A global HMI has been developed and integrated. This global HMI is able to guide the operator of the two cells which comprise the entire demonstrator. This HMI demonstrates the capability to perform monitoring in the same HMI, showing different parts of the line composed from different standards and suppliers.

Section 4: Potential Impact

Impact

From a strategic standpoint, the PRIME project contributes to the thematic area of New Production Technologies, specifically FP7 FoF.NMP.2012-3 Intelligent Production Machines and Plug and Produce Devices, where the expected impact of self-learning production systems is expressed as: "*Standardisation and developments in 'Plug-and-Produce' should lessen the commissioning effort and ramp-up time whilst enhancing context-awareness, maintainability, modularity, re-usability, safety and versatility of manufacturing systems*". PRIME is an essential step towards achieving this target.

Results achieved and validation exercises performed on the PRIME demonstrators using specific test case scenarios indicate support towards the proposed strategic impacts:

Reduction in time and effort of manufacturing system installation. Commissioning and ramp-up

- Reduction in time required to install process modules by 50% through use of standardised software interfaces and a common architecture, providing time savings in the overall installation process.
- Standardised software interfaces and guidelines to support ramp-up and commissioning of assembly systems.
- Use of a combined toolbox and services approach to allow efficient and effective deployment of advanced control systems

Enhanced context awareness, modularity and re-usability of manufacturing systems

- Enhanced ability of system to contextualise and support self-awareness and self-adaptation through the integration of a behavioural model.
- Pro-actively support system module planning activities to maximise module re-use.

Improved maintainability, safety and versatility of manufacturing systems

- Reduction in software error rates through employing standardised software interfaces and increasing system reliability.
- Use of behavioural model to pre-emptively assess system maintenance requirements and facilitate an accurate maintenance schedule via data analysis module.

The impact results from each of the demonstrators are detailed below:

Demonstrator 1: showcased the communication infrastructure of the underlying multi-agent system, which integrates plug and produce functionality.

- **PRIME reduces the configuration time by 50%** - Building up the system from scratch involves plugging in seven components, which typically takes 15 minutes. PRIME's plug and produce technology reduces this time to no more than seven minutes.
- **PRIME reduces the risk of introducing errors during reconfiguration** – The PRIME system automatically detects all devices after they are plugged in, and modifies the corresponding recipe files, which are used to configure the associated control logic. Since this process is carried out with no operator intervention, the probability of introducing an error is minimised.

- **PRIME simplifies the user interaction to a non-expert operator –** This is related to the previous item. Since relevant control files are configured by the PRIME system, operator intervention is minimal. This allows an inexperienced operator to build up a whole system from scratch.

Demonstrator 2: showcased a complete plug and produce cycle, which sets up the control system in order to assemble a product or its associated variants.

- **PRIME significantly reduces ramp-up and configuration effort by minimum 80% –** The PRIME system detects each assembly device in less than a minute, and atomic capabilities are aggregated continuously. On the other hand, the operator enters product definitions using the HMI. Product definition – complex capability matching is performed in no more than one minute. The length of this procedure contrasts with that of a standard assembly system for which the ramp-up would take between five minutes and two hours. The longer time and larger variance of the standard procedure make the PRIME system a competitive system.
- **PRIME reduces the cost of recovery from failure -** After a failure, remaining production devices are detected, and faulty devices are deregistered from the PRIME system automatically. The remaining set of complex capabilities can be matched against a given product definition. After this, the PRIME system informs operators about missing capabilities and production can be re-started. Recovering from a failure in a standard control infrastructure lies in the range of 6-8 hours.
- **PRIME simplifies the process of introducing product variants -** Flexibility is realised by redefining assembly steps in terms of complex capabilities of the assembly system. This is significant when dealing with a range of product customisation variants.

Demonstrator 3 - implemented the monitoring and data analysis functionality of PRIME. Integrating the HMI module within the Monitoring and Data Analysis Module in the PRIME architecture resulted in a monitoring and data analysis system supported by a multi-agent system, a data-stream processing network, and a database management system in the back-end. The front-end is a HMI that allows the operator to monitor and analyse data related to cycle time, parts count, door state, emergency buttons, safety state, scanner state, and barrier state.

- **PRIME reduces integration costs by 10% –** Analysis of the behaviour of relevant time series can be performed in-house before integration, which reduces integration costs up to 10%.
- **For OEMs PRIME reduces downtime due to equipment breakdown –** This impact is not yet quantifiable at this moment as it is dependant on maintenance plans and their execution.
- **PRIME improves the overall cost effectiveness of the assembly line** – the data collection and pre-processing of production line behaviour patterns supports cycle time optimisation, detection of faulty processes and speeds up the overall commissioning phase. This provides cost savings through reduction in resource usage and lessening of expert effort in early integration phases.

‘The PRIME outcomes will facilitate the creation of a new generation of rapidly configurable, self-aware, evolving and adaptive assembly systems that are much easier to deploy, can proactively cooperate with human operators and machines to adapt during ramp-up and can react faster to fluctuations and disruptive events.' This decreases system ramp-up times and downtimes, leading to increasing productivity and yield. Also, the reduced deployment effort through more responsive systems and shorter production times enable the creation of the foundations for the successful system-to-service transformation from static capital-intensive production lines towards using dynamic assembly services on demand.

PRIME aims to remove the barriers preventing SMEs from implementing 'plug and produce' through standardisation, legacy compliance and focussing of expertise. Additionally, the PRIME approach ensures cost-effectiveness of all developments, thereby ensuring SMEs will be able to access and implement the developments. The PRIME approach supports this cost-effective modularity through standardisation, an open architecture and development and integration guidelines. PRIME enables a substantial compression in the time required to reconfigure a manufacturing system for production of a new or revised product. This results in cost-effective low-volume production and thus opens manufacturing opportunities to companies with limited resources.

Exploitation and the Road towards Commercialisation

A number of tools and features encompassed within the PRIME Architecture have been both developed, and investigated, during the project. Four exploitable results have been identified for further dissemination within the industrial world:

1. PRIME Software Toolbox (HMI, Plug & Produce, Monitoring and Data Analysis)
2. PRIME for Plug & Produce (Plug & Produce, Production Components Module)
3. PRIME for Monitoring and Data Analysis (Monitoring and Data Analysis Module)
4. System for Processing Streams of Data (Monitoring Daemon)

Whilst the focus of the PRIME project has been on the benefit to European SMEs, a thorough analysis of recent market trends in global automation and flexible automation has been performed in order to understand the potential impact of PRIME on industrial manufacturing infrastructure. It is shown that different sectors are confronted by the same issues: flexibility and reconfiguration.

PRIME Toolbox

As agreed in the PRIME consortium, the PRIME Software (SW) Toolbox is the key exploitable deliverable of the project. It is a collection of SW Tools which support automation engineers in setting up industrial automation solutions, assists with optimising system configurations, simulates and optimises performance, and enables rapid process setup. It contains the following modules:

- HMI Module
- Plug & Produce Management Module
- Monitoring and Data Analysis Module
- Production Components Module
- Support libraries (Blueprint, OPC, Cassandra)

This product is not a completely finished SW package addressing an entire industrial application segment. As such the established commercialisation route through SW Licensing at an appropriate pricing would create a significant hurdle to many potential customers and application experts. As all potential future exploitation of the PRIME SW Toolbox crucially depends on successful capture of an early niche adopter, the consortium agreed to offer the entire PRIME SW Toolbox in the form of Freeware (i.e. license-free downloadable code without entry barriers). The path towards commercial exploitation will commence with consortium partners offering consulting services for implementing the PRIME toolbox.

Location

The PRIME System Integrator Toolbox (binaries only) containing basic documentation can be downloaded from the PRIME website (www.prime-eu.com/downloads) free of charge.

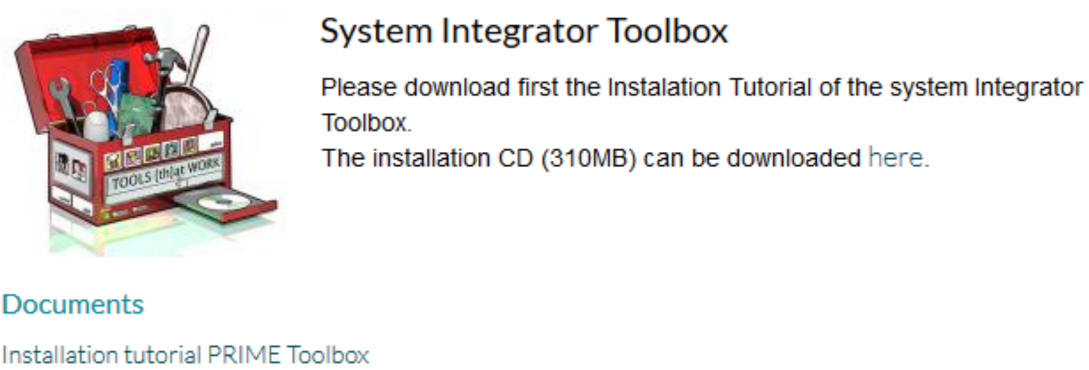

Figure 15. PRIME System Integrator Toolbox as displayed on the PRIME website

The toolbox is available on the internet for interested users free of charge. In depth discussions on alternative scenarios have been delayed by the consortium based on an initial cost-benefit analysis. The access details for the freeware is an integral part of the PRIME dissemination process and has already been promoted at the National PRIME days[1].

[1] University of Nottingham in cooperation with TQC, 30.09.2015
INTROSYS in cooperation with UNINOVA, 08.10.2015
ZHAW, CSEM in cooperation with Asyril and Simplan, 15.10.2015

The source code is available in the repository for all partners and is expected to be built upon through future cooperation within the consortium. No source code is available outside the consortium but future cooperation within the consortium is promoted to improve and evolve the publically available PRIME toolbox.

Price

As detailed above, the PRIME SW Toolbox will be promoted as Freeware (i.e. open access to executable SW code from an internet server without the source code). This also corresponds with a slim administrative effort as no invoicing, billing and other related financial administration will be put in place at this stage of market access. The consortium agreed that the end user market being willing to pay for such SW at this stage would not be large enough to justify the infrastructure and administrative effort required to handle the financial transaction.

Promotion

Promotion (or dissemination) is an integral part of an operational marketing plan for any product or service. The dissemination effort in the case of the PRIME Toolbox has to be strictly confined to the target expert user group within industrial automation, characterised by the following skillsets:

- Technical expertise in agent based automation SW
- Willingness to work with PC based automation and setup tools
- SMEs with top management support to incorporate advanced SW methodologies
- Open mindset toward working with mature PLC components and advanced innovative higher level (not real time) control and configuration architectures
- Active members of industrial expert networks linked to research and academic institutions both in Europe and worldwide
- Industry innovation networks willing to promote Industrie 4.0 skillsets to all interested companies

The PRIME consortium firmly believes that the current SW modules in the toolbox are not a finished product but an attractive entry-level productivity tool that has the potential to grow a lead user application expert base in Europe. A detailed route towards the industrial automation market has not been defined at this early stage. Further involvement from end users across multiple sectors will be sought to progress market acceptance. The commercial success of the PRIME Toolbox will be an iterative step-by-step adoption and will crucially depend on satisfied early adopters. This is a process that cannot be planned but will be proactively supported by all PRIME consortium partners with a vested interest in further development of the skillset that will enhance automation setup efficiency in industrial production. Linked to this, each member of the consortium has developed individual 'road to market' business cases to capitalise on their involvement in developing the PRIME Toolbox.

Section 5: Address of Public Website and Contact Details

Website

http://www.prime-eu.com

Contact Details

Project Coordinator:
Professor Svetan Ratchev
Svetan.Ratchev@nottingham.ac.uk

Administrative Queries:
Ms Bethany York
Bethany.York@nottingham.ac.uk