A distributed control architecture for a reconfigurable manufacturing plant

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***Abstract*—This work presents a novel approach for the implementation of industrial Cyber-Physical System (CPS) based on the integration of the IEC 61499 international standard for distributed industrial automation, as conceived in the DAEDALUS Horizon 2020 project. Among the different innovations introduced by the project, this work focuses on the establishment of internal cognitive functionalities: a Function Block for model-based optimal control is devised for the optimal orchestration of CPS. As a case study, the automation of a lab-scale industrial plant for End Of Life treatment of electronic circuit boards is developed with the proposed methodology. The plant orchestrator is a validated Hybrid Model Predictive Control solution. It is shown how it is possible to model complex systems, creating aggregated structures of CPSs, and to orchestrate them thanks to the distributed intelligence. The completion of the software development kit for a seamless development of optimal orchestration and logic control is the final objective of the ongoing project.**

***Index Terms*—Cyber-Physical System, IEC 61499, Optimal Control, Hybrid Model Predictive Control, Distributed Control Architecture, Manufacturing plant.**

I. Introduction

Boosting the efficiency, flexibility and productivity of manufacturing plants is the industrial challenge of next years, in order to increase the competitiveness and lead the global market [1]. European industries are infact progressively evolving from traditional mass production to mass customization. To meet this goal, the production systems must be designed to support flexibility and fast reconfigurability. As well, the control architecture must follow the same principles. The traditional paradigm of industrial automation is not satisfactorily suitable to keep the pace with the novel requirements of such evolving business scenario. A distributed and networked control architecture opens the way towards a flexible, scalable and reconfigurable production system.Further to this, control distribution must rely on the interconnectivity of embedded smart devices and the effort of digitalization driven by the paradigm of Industry 4.0. The concept of Cyber-Physical Production Systems encapsulates all the peculiarities needed to address a novel distributed automation. In the vision of CPS framework, every component of the production system is represented in its physical and digital counterpart, where the participation in a unified environment enables the interaction and collaboration with any of them.

Nowadays, several open research issues have been tackled in the definition and realization of CPS [2]: cyber-physical systems are conceptually characterized by being a network of distributed intelligent and modular entities able to interact in an adaptive and collaborative way. Different approaches have been proposed in the last years in various research actions, some how paring the way to CPS paradigm as reviewed in [3], [4]: Multi-Agent System (MAS) framework enables the capabilities of self-adaptation and the creation of emerging behaviours thanks to agent interaction in a network of cyber-physical components. Other approaches consider Service-Oriented Architecture (SOA) [5], to support the interaction of smart embedded devices with high interoperability and also as a integration of the MAS framework, to extend the interoperability of the distributed entities. On the other hand, Holonic Manufacturing Systems (HMS) constitute a further approach supporting smart, reconfigurable and distributed architecture that dates back to [6], [7]. Holons, composed of an information processing part and a physical processing part, paved the way to the concept of CPS. Holons can create groups of cooperating entities dynamically to target a common goal by the interaction of their information/logic processing part. By the holonic principle, complex systems can be built as a composition of simpler holons. However, the responsiveness of these approaches is a severe issue for real-time applications. To address this problem, [8] proposed to integrate the agent framework with the advantages of function block concept of the international industrial automation standard IEC 61499 [9]. A two-tier entity was defined: a higher level implementing MAS architecture, communicating with FIPA protocol for inter-agent communication and enabling negotiation and intelligence and a lower layer dealing with system real-time responsiveness, implementing PLC-based automation logics. Also, the work proposed in [10] combines the holonic and agent concepts with function blocks focusing more on the requirements of the lower level and introduces an hypothetic manufacturing CPS.

This work presents the methodology conceived according to the vision of the H2020 EU project DAEDALUS, which proposes the industrial automation standard IEC 61499 as the framework for the development of a distributed control solution for the application of the CPS paradigm. It focuses on the conception of a flexible, reconfigurable and intelligent architecture and on the realization of the tools empowering

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automation engineers to design and deploy advanced solutions in this framework. The cornerstone of this work is the adoption and extension of the already industrially validated IEC 61499 framework, with the appropriate addition of innovative functionalities, concretely enabling the deployment of real-time cyber-physical systems in production environment, defying the currently rigid hierarchical levels of the automation pyramid towards its full virtualization. Moreover, Daedalus proposes the extension of the capabilities of current IEC 61499 function blocks to enable the deployment of an orchestrating intelligence implementing multidisciplinary optimization algorithms. The de-facto standard approach for real-time optimal control of constrained highly complex systems is the Model Predictive Control (MPC). This work shows how Daedalus intends to enable this advanced control system solution within a distributed platform. Today, industrial automation standards, even the IEC 61499, do not support the development of MPC solutions. This work aims at introducing a MPC-based Function Block that provides optimal control capabilities.
Daedalus approach exploits the characteristic composability of the function block architecture to conceive aggregation of equipment and devices to generate more complex systems supported by a progressive orchestration of their behaviour.
This paper presents, through the application on a lab-scaled industrial plant for the End Of Life (EOL) treatment of electronic boards, the ”De-manufacturing Factory” (DMF), the evolution and the expectations of the Daedalus initiative, in particular, the potentialities of the extension of the IEC 61499 function blocks for the coordination of cyber-physical systems. As regarding the CPS Orchestrator of the plant, Hybrid Model Predictive Control developed by [11] is considered.

The paper is organized as follow: Section II presents the integration of IEC 61499 and its advantages. Section III describes the ”De-manufacturing Factory” and its control problem. While in Section IV is reported the implementation on field level of the proposed distributed architecture, Section V is devoted to describe the MPC control problem by presenting the Mixed Logical Dynamical (MLD) formulation of the dynamic model. In Section VI is shown the integration of optimal orchestrator as a IEC 61499 Function Block. Section VII draws conclusion and hints for future works in order to improve the proposed solution following the evolution of IEC 61499 standard.

II. DAEDALUS IEC 61499 IMPLEMENTATION OF CPS

In the vision of Daedalus project, the technological needs of the next future industrial automation sector are addressed by the conception of an Automation Ecosystem based on a new generation of distributed intelligent devices, cyber-physical systems, which can be aggregated, orchestrated and re-configured to exhibit complex manufacturing behaviours.
The CPS implementation envisioned here is based on the adoption of a completely distributed automation platform extending the IEC 61499 standard. Currently the standard offers already powerful and interesting features: i) a modern interoperable event-based object-oriented development language; ii) interoperability between devices; iii) real-time communication among distributed systems; iv) hardware abstraction; v) automatic management of low-level variable binding between resources vi) possibility of debugging the entire automation project of the plant up to low level control from a single console.

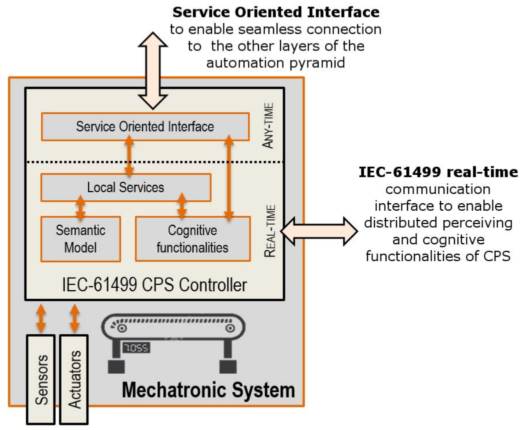

Fig. 1. Daedalus CPS representation according IEC 61499

Daedalus project aims to enhance the functionalities of this standard, adopting a functional model for the implementation of CPS that blends coherently real-time coordination of its automation tasks with the ”anytime” provision of services to other elements of the automation pyramid. The extension of the model is shown in Figure 1. The digital counterpart of the Daedalus IEC 61499 CPS includes not only the control algorithms but also the other digital facets of the system, e.g. the HMI, the behavioural models and hardware abstraction. The integration of the Service Oriented Interface enables the full exploitation of the CPS virtualized intelligence concept, empowering the connection to any other digital module, e.g. simulation modules offered as a service.
This work focuses in particular on the definition within the CPS of the cognitive functionalities, enabling system orchestration and optimal control. Among the advanced control strategies, the Model Predictive Control stems out for its capabilities of optimizing system performance while imposing explicitly the respect of process constraints. In particular, Hybrid MPC is implemented, due to the discrete nature of the manufacturing plants addressed by the project. The hybrid framework allows to describe the interaction between continuous and discrete/logic variables.
Daedalus CPSs can be hierarchically aggregated to form complex systems and represent entire production cells/lines. The inclusion of smart capabilities in every cyber-physical system enables the coordination of aggregated systems of CPSs. In order to control a wide plant or a sophisticated network, an optimal control technique as MPC is essential. Daedalus proposes a Software Development Kit, to be integrated in the 61499 IDE (Integrated Development Environment), to support automation engineers in the design of optimal orchestrator. Straightforwardly, CPS paradigm leads to a new generation

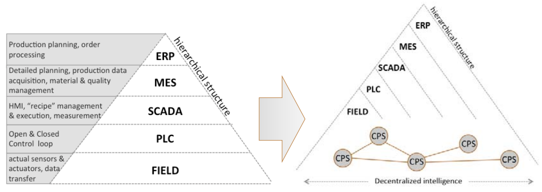

Fig. 2. On the left ISA-95 pyramid and on the right CPS approach

of knowledge based solutions, capable of integrating and handling data of all factory levels in a comprehensively structured real time framework, from machines controls up to shop-floor supervision and production planning [12]. The suggested solution goes beyond the limits of current PLCs means, establishing a new generation of embedded control devices, showing the potentiality of the adoption of a complete distributed control architecture with a deeper interconnection between different control levels, from the ERP to the field through MES, SCADA and DCS levels.

The advantages of this approach to industrial automation have to be highlighted. Until now the automation of production line has been usually built up following the evolution of classic ISA-95 pyramid (see Figure 2). In this way the different level are interconnected but not designed in a harmonized way. The presented approach allows a full integration between different control levels with a distributed intelligence along production line. For this reasons the CPS concept, see Figure 3, will be able to introduce industry to I4.0 paradigm, where each components of the production line is smart and able to communicate with all control levels. The aforementioned architecture of System of CPS is shown in Figure 3. Each single CPS runs in a computation device, a PLC for simple components or an Industrial PC (IPC) for more complex aggregation or for orchestration, with a Linux real-time distribution and a IEC 61499 framework, e.g. NXTcontrol.

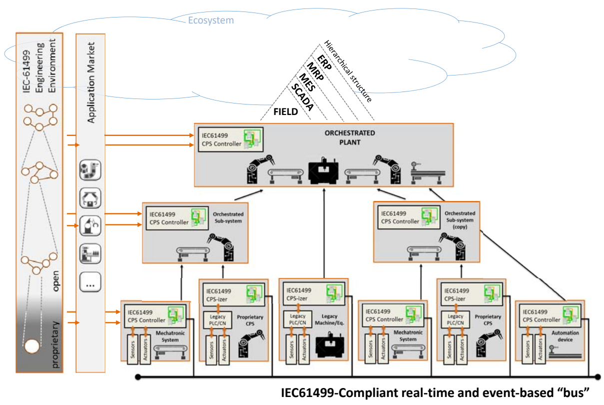

Fig. 3. Full CPS production line

III. Case of Study

This work presents the development pathway of the Daedalus IEC 61499 CPS approach through its application on a lab-scale industrial case study. The aforementioned framework is used to design and deploy the low-level control, as well as the plant orchestration.

ITIA-CNR "De-Manufacturing Factory" (DMF) represents a pilot plant for the integrated End-Of-Life (EOL) management of mechatronic products by means of modular technological solutions conceived to be capable of processing heterogeneous products with a limited hardware and software reconfiguration effort. In particular, the process have been conceived to recover the maximum value from the products. Therefore, the first objective is to give a second life to the overall product by re-manufacturing. If not feasible, due to technical or economic reasons, the second option is to give a second life to the product components by proper disassembly. The final option is to recover at least the product material, thus replacing actually adopted policies based on incineration and landfill [13]. In fact, as reported in [14] a sustainable optimal de-manufacturing approach was not adopted by companies until now due to the lack of economic viability of the available processes and technologies for the implementation of the most favourable strategies of EOL. Within the DMF, the electronic printed circuit board (PCB), first disassembled in a robotic station, is then mounted by the robot on a pallet and loaded on an automatic transport line, composed by 15 modular conveyors, aimed at transporting PCBs on the operating stations of the re-manufacturing process. Main process operations include:

- PCB circuit analysis, aimed at identifying eventual corrupted components on the board;
- PCB rework, aimed at replacing corrupted components;
- PCB material recovery by shredding and material separation machines.

The current layout of the plant include a single station for each of the above processes. Nevertheless, the DMF plant has been designed to support different production scenarios. The PCB routing and process sequence is not pre-determinate: the circuit analysis machine, which determines whether is worth repairing the PCB or recovery components or material, defines the sequence of operations. To solve the DMF scheduling problem, in [15] a particle swarm optimization is presented.

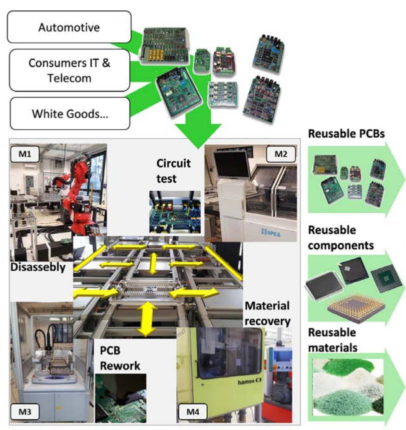

Fig. 4. De-manufacturing plant description

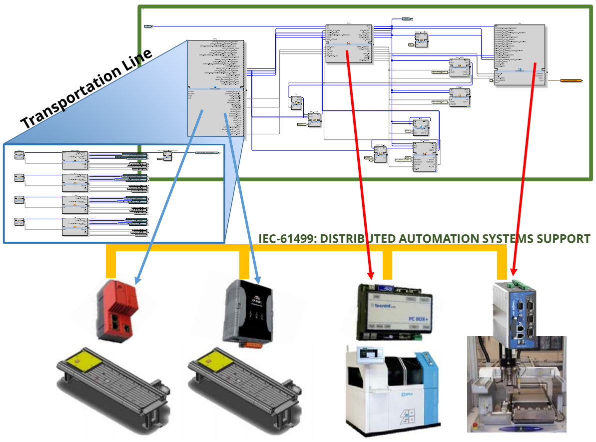

Fig. 5. De-Manufacturing control architecture compliant with IEC 61499

Beside, a dynamic orchestrator must be in charge of governing the overall plant, based on the defined task sequence.

IV. DAEDALUS CPS WITHIN LINE AUTOMATION SYSTEM

The re-manufacturing process automation system has been developed in the IEC 61499 framework, namely nxtSTUDIO [16], supporting the development of a fully distributed automation systems [17]. As described in [18], where the DMF plant is exploited to show the CPS Virtual Avatar as enabler of the virtual commissioning, the control system hardware architecture has been structured by assigning a dedicated embedded controller to each module of the DMF plant. Thanks to the resource-based distributed application support and the automatic binding features provided by the IEC 61499 standard, it is possible to manage the overall control solution as a unique program. In fact, despite IEC 61131-3 based technologies [19], which require to manage each hardware controller with a dedicated control program, IEC 61499 based technologies are capable of automatically downloading the application code within the distributed hardware architecture, generating automatically the exchange variables mappings, radically reducing the effort for commissioning, managing and reconfiguring complex distributed control applications. A control logic block for each functional component of the re-manufacturing process has been defined according to its modular composition and to control functionalities. Each function block exposes:

- an event type input request for each task (i.e. automation function) the module is capable of performing;
- a data type input for each configuration parameter related to tasks execution of the module;
- an event type output for each module task execution acknowledgement (including un-nominal and failure conditions) and for each request for task execution towards subsequent modules;
- a data type output for each variable representing the module internal state and tasks execution.

Coherently to this, the IEC 61499 function block related to operating machines (e.g. rework, circuit testing, etc.) exposes a $LOAD_{PCB}$ (load board in the machine) event input connected to an input integer data PCB_{ID}. When the load task is called by the event, the identification code of the pallet is passed to the machine by PCB_{ID}. Such code is then used by the control logic of the machine to upload from the production system database the operation program to be performed on the specific PCB (i.e. operating temperature for re-flow, current/voltage levels to be used for components testing, etc.). When the operation is completed the machine FB generate an event output asking for board download to the conveyor.
Based on these elements, the work addresses the extension of the IEC 61499 standards to enable the development and deployment of model-based optimal controls in the same framework, as CPS Orchestrator Function Blocks. The function blocks exposing the automation tasks (related to conveyor transport tasks or machine operations) of the re-manufacturing line are then connected to a function block (named Orchestrator FB) aimed at calculating the path and sequences of operations (automation tasks) to be performed. Such function block is aimed at calculating in real-time the sequences of automation tasks to be performed by the line depending on run-time varying operating conditions. As soon as a task have been started, the IEC 61499 FBs then interacts by exchanging synchronization signals (as events and data) required for task execution.

V. OPTIMAL ORCHESTRATOR

According to [20], [21], the pallet can be moved step by step towards the transport line by means of low level logic control sequences. By defining specific control variables uniquely associated to the pallet movement between two positions on the transport line, called Buffer Zone, the de-manufacturing plant can be represented as a directed graph with nodes $N_1 - N_{31}$ and arcs, see Figure 6. The nodes represent both the Buffer Zone $\Upsilon_{i,j}$ (circles) and the machines

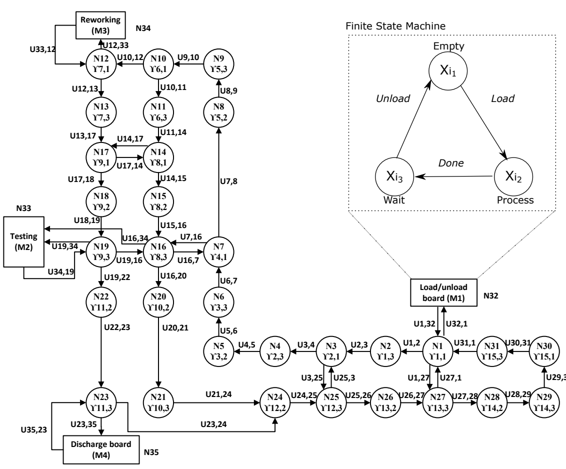

Fig. 6. Direct graph representation of the plant. In the upper-right corner, the Finite State Machine of the internal behaviour of the machines

M_i (rectangles $N_{32} - N_{35}$) where the pallet can lay, while the arcs are associated to the orchestrator commands, $u_{i,j}$ where $i, j = 1, \ldots, 35$, used to move the pallet from node N_i to node N_j, according to the specific transport line topology, define the set I_u. Each station M_i is modelled with a Finite State Machine (FSM), describing its re-manufacturing process. For convenience, these nodes are progressively numbered and labelled $N_1 - N_{35}$. Specifically the buffer zones $\Upsilon_{i,j}$ are labelled $N_1 - N_{31}$, while the machines $M_1 - M_4$ are tagged $N_{32} - N_{35}$. For example, the command $u_{2,3} = 1$ is used to move a pallet from $N_2(\Upsilon_{2,3})$ to $N_3(\Upsilon_{2,1})$.

A. Hybrid Model Predictive Control formulation

The dynamic model of the transportation line and of the machines, described in detail and validated in [11], is translated into the MLD formulation by linearizing the non-linear terms and the logic propositions [22]. Then the HYSDEL tool [23] is used to generate the MLD model described by:

$$x(k+1) = Ax(k) + B_u u(k) + B_\delta \delta(k) + B_z z(k) \quad (1a)$$

$$y(k) = Cx(k) + D_u u(k) + D_\delta \delta(k) + D_z z(k) \quad (1b)$$

$$E_\delta \delta(k) + E_z z(k) \leq E_u u(k) E_x x(k) + E \quad (1c)$$

where x is the vector of the state variables, u is the vector of the control actions, with elements $u_{i,j}$, while δ and z are the vectors of Boolean and continuous auxiliary variables, used to define the process and logical constraints of the system. The performance index to be minimized at any time instant k with respect to the future control actions defined over the prediction horizon specified by the positive integer N_{RH}, is given by:

$$J = \sum_{h=1}^{N_{RH}} \left\{ \sum_{i=1}^{31} c_i \left(Tp_i(k+h) \right) + \sum_{i=32}^{35} \left(q_i \cdot X_{i3}(k+h) \right) + \sum_{(i,j) \in I_u} Q_u \cdot u_{i,j}(k+h-1) \right\} \quad (2)$$

The first term Tp_i takes into account the distance of a pallet from its target machine, so to allow the control system implementing the pallet movement along the transport line to minimize the transfer cost toward the target machine, while second addend penalizes the permanence of a pallet in a machine after the completion of the process, X_{i3} of the FSM. Weights c_i, q_i must be defined opportunely. The control actions $u_{i,j}$ are weighted in J through the positive coefficient of the matrix Q_u to avoid not useful pallet movements. Finally, N_{RH} must be selected large enough to avoid possible deadlocks due to conflicting paths of the pallets and not exceed the minimum among the number of steps required from the machines M_i to work the pallets. The performance index (2) must be minimized under the physical and logical constraints described by the MLD model (1). Then, once the sequence of optimal controls $U^{\text{opt}}(k) = [u_{i,j}^{\text{opt}}(k), u_{i,j}^{\text{opt}}(k+1), \ldots, u_{i,j}^{\text{opt}}(k + N_{RH} - 1)]$ has been computed, according to the Receding Horizon approach, only the first value $U_1^{\text{opt}}(k) = [u_{i,j}^{\text{opt}}(k)]$ is applied and the overall procedure is repeated at the next time step.

VI. Orchestrator in IEC 61499 environment

For control system deployment, a distributed Industrial PC (IPC) architecture has been adopted, connected by an Industrial Ethernet communication infrastructure. Each IPC integrates a NXT IEC 61499 run-time environment running on Linux RT operating system. NXT environment provides all the software facilities for reading and writing physical I/O signals, execution of the control logic programmed by IEC 61499 function blocks (FB) and data exchange between the controllers during runtime execution. Then, each unit of the line (including rework station, circuit tester, etc.) has been represented and coded as an IEC 61499 FB exposing the supported automation tasks (e.g. transport task, PCB rework, etc.) as invokable inputs and the station run-time state (e.g. idle, executing task, task completed, maintenance, etc.) as readable outputs. The operating unit FBs are then connected to the Orchestrator IEC 61499 FB implementing the optimization algorithm and deployed within the re-manufacturing line automation system as summarized in Figure 7. Such FB is executed on a dedicated Industrial PC integrating an NXT run-time including an interface for calling external functions developed in C++. In particular, Optimal Orchestrator FB integrates an internal function calling the model based optimization algorithm library for on-line re-scheduling operations, as described in section V.
The Orchestrator FB implements the following execution logic. During line start-up, the Orchestrator FB runs in idle mode, checking for events from the Production Line Manager about new jobs list to be processed. Then, the availability of units needed for job tasks execution are verified, by sending a task event request and waiting for actual state message. Therefore, the optimization C++ function is executed. The optimization consists in a recursive solution of Hybrid Model Predictive Control algorithm, detailed in section V-A. The MPC algorithm reads the input from the plant in terms of pallets target and position, formulates the MLD model by building the dynamic and constraints matrices and call the

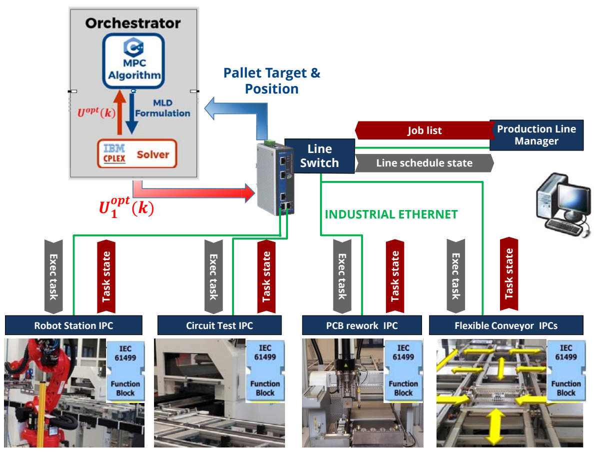

Fig. 7. Implementation of optimal orchestrator within the line automation.

CPLEX optimization function in order to compute the optimal control sequence $U^{\mathrm{opt}}(k)$. Once the optimal control sequence has been calculated, the first component $U_1^{\mathrm{opt}}(k) = \left[u_{i,j}^{\mathrm{opt}}(k)\right]$ is extracted by the MPC algorithm and sent to the plant. At the end of the optimization procedure, indeed, the overall best solution is provided as the final solution of the problem to the calling FB. Then, task execution message (including data about PCB_{ID} and task timing) is sent to the scheduled units. Afterwards, the Orchestrator FB continuously monitors the state of each components of the line and is able to react at external or internal disturbances, as rescheduling request from production line manager, routing problem or any other issue.

VII. Conclusion and Next Steps

To face new consumer centred manufacturing paradigms, like mass customization and personalization, factories must be capable to adapt in real time to continuously changing market demand. Thus, the whole production cycle for small or even single batches has to be executed in very short times, i.e. a few days or even hours. Manufacturing process behavior has to be optimized in real-time, so to minimize production costs. Moreover, agile production system reconfigurability has to be properly supported. To tackle these challenges, new control system architectures have to be provided to industry, supporting modularity, distribution, openness and efficiency. Daedalus project is developing a novel control architecture, exploiting the integration of IEC 61499 technology and Model Predictive Control techniques. A major objective is to offer an industrial level support to model and implement both the low-level control modules and the system orchestration.

De-manufacturing process use-case scenario has been reported in order to illustrate the foreseen application of Daedalus technology to an industrial production system.

The proposed methodology, with the integration of optimal orchestration capabilities and the composability of the function block architecture, offers the possibility of aggregating structures of CPSs to control and orchestrate complex systems. The potential additional burden required for the formalization of the control solution in the IEC 61499 framework is compensated by the reduction of automation engineer efforts for system reconfiguration thanks also to the manageability of the entire project from a single station.

A major open issue regards the lack of native support within the available IEC 61499 platforms of software facilities for design, development, validation and integration of Model Predictive Control systems. Planned developments for the next two years of Daedalus project rely on the realization of a Software Development Kit supporting MPC-based orchestration implementation within IEC 61499 framework. Moreover, distributed MPC techniques have to be exploited to be properly integrated within the development roadmap.

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