Smart Appliances and RAMI 4.0: Management and Servitization of Ice Cream Machines

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Abstract[1] **— The widespread adoption of Information and Communication Technologies (ICT) is profoundly changing manufacturing. Several Internet-of-Things (IoT) and Industry 4.0 solutions deployed in production environments have pushed for standardization efforts, most notably Reference Architecture Model Industrie 4.0 (RAMI 4.0), typically focusing on smart factory environments. However, ICT evolution is also enabling novel smart appliance scenarios, where relatively cheap machines, connected and integrated, are deployed outside the typical industrial environment with a wide range of stakeholders involved. The paper reports about a real-world use case composed of more than 12000 ice cream machines connected worldwide and shows how, anticipating the state-of-the-art, the underlying design of the ICT platform presents many interesting similarities with RAMI 4.0. The integration of appliances in a smart value chain enables to develop novel services for different stakeholders, ranging from ice cream manufacturer and maintenance technicians to ice cream shop owners and final consumers. The important synergies with RAMI 4.0 and the extensive on-the-field validation make the proposed solution a compelling reference application, from which to draw useful and generally applicable guidelines for the development of future Industry 4.0 smart appliance platforms.**

Index Terms—**Internet of Things, Intelligent manufacturing systems, Industry 4.0, Smart appliance.**

I. Introduction

INDUSTRY 4.0 started in Europe several years ago to embed new Information and Communication Technologies (ICT) into the factory. Industry 4.0 traditionally refers to smart plant environments, where information technologies interconnect all heterogenous components within a factory to propose a new way of managing entities in the shop floor. More recently, also thanks to the Internet-of-Things (IoT) revolution, the area of *smart appliance* attracted attention, thus enlarging the boundary of the industry plant to the outside world, so to consider machines deployed everywhere outside the plant.

Smart appliances represent a platform to build a large assortment of novel services, starting from the remote control of machines to more sophisticated add-ons that can more easily adapt to the operation context. In this scenario, one of the most promising services is e-Maintenance, which exploits machine remote management capability to allow technicians to remotely interact with devices to investigate their current and past state and also to modify their configuration and to update software modules [1]. This allows to fix basic problems and to more effectively address serious issues by identifying broken components and consequently plan on-site interventions with the required spare parts. In addition, e-Maintenance allows the adoption of *predictive maintenance* approaches that can automatically early detect degrading performance in smart appliances, likely to lead to upcoming malfunctions, and consequently schedule assistance interventions to minimize repair costs, revenue losses, and machine downtimes [1, 2].

The smart appliance scenario also paves the way to the adoption of *new business models and opportunities*, that are better aligned to the needs of vendors and consumers [3]. In fact, smarter after-sale assistance practices, with significantly lower costs, suggest to consider *pay-per-use contracting*, or *servitization*, for smart appliances. In case of smart appliances that process consumables, e.g., coffee capsules, vendors can propose *smart supply chain services*, so to suggest consumers to refill their stock of consumables not only based on the number of remaining capsules, but also considering per-product and aggregated consumption patterns, and contextual information, e.g., a cold weather forecast might lead to more coffee consumption.

The paper presents how the adoption of a *smart appliance* perspective has totally modified the ice cream machine business field of Carpigiani, a global producer of professional ice cream machines and supplier to many of the world most important restaurant and fast food chains. Along this direction, the contributions of this paper are manifold. First, it provides a high-level presentation of issues and benefits of adopting emerging Industry 4.0 solutions and standards in (relatively) small smart appliances from a business model perspective. Second, it presents the Carpigiani solution, called Teorema, for ice cream smart management as an archetypal and relevant real-world and large-scale global use case of smart appliance management that consists of more than 12000 ice cream machines worldwide. Third, it discusses how, while anticipating the industrial state-of-the-art, Teorema presents many interesting similarities with the models and best practices proposed by the noteworthy and emerging Reference Architecture Model Industrie 4.0 (RAMI 4.0) [4]. The important synergies between Teorema and RAMI 4.0 allow to

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formulate important and general guidelines: they confirm the broader applicability of models and concept developed within RAMI 4.0 for smart factory scenarios to large scale smart appliance applications. Fourth, it shows Teorema effectiveness in both promptly detecting unpredictable failures and early warning in case of performance drifts.

II. Industry 4.0: from Smart Factory to Smart Appliance

Traditionally, Industry 4.0 targets the smart factory scenario and considers machines as part of production lines in the shop floor. In fact, many Industry 4.0 use cases target smart factory scenarios with huge and expensive Internet-enabled smart machines, typically deployed in a concentrated fashion and managed on-site by skilled technicians that can fix simple misbehaviors/failures. However, we claim that Industry 4.0 concepts can also be fruitfully applied to smart appliance scenarios, characterized by cheaper and smaller machines deployed in locations well outside the controlled factory boundary and sometimes even isolated, where little or no technical personnel is available for their management. Let us note that such smart appliance scenario has been recently enabled by the commoditization of sensors and powerful embedded software/hardware stacks. That makes true the promises of IoT by enabling remote monitoring and control of physical objects, traditionally locally managed by humans, as fully-digitalized entities connected to the Internet.

This is the case of Carpigiani ice cream machines, small-to-medium size appliances (if compared with production lines in factories) deployed in ice cream shops in several countries and eventually relocated without any knowledge. Notwithstanding their smaller size, ice cream machines perform non-trivial processes: ingredients need to be mixed together, pasteurized, homogenized, cooled, and pumped into a scraped-surface freezer, where about 50% of the water is frozen and air is incorporated into the product. Upon exiting the scraped-surface freezer, inclusions and variegates may be added, and the final product is filled into its container [5]. Mechanical and electronic components have to be designed and developed for this specific purpose, imposing the intervention of specialized technicians in case of maintenance procedures. More generally, consider the case of household/industrial appliances ranging from top-level washer-machines, ovens for bakeries, and fridges for hospitals, to remotely monitored and controlled tractors for precision agriculture. These relatively small and less expensive smart appliances may be very complex and with high-duty systems with a long life-cycle (usually more than ten years) that requires on-site maintenance interventions, usually very expensive for both technical personnel costs and (possibly long) machine downtimes with related revenue loss.

In sharp contrast with the smart factory scenario, we claim that the smart appliance scenario is characterized by three primary aspects:

- *global scale*: a great number of machines is distributed worldwide and the final location of machines is not under control to the manufacturer/vendor, since the end-user can easily relocate them several times;
- *unattended machines*: personnel directly using machines can only use few of the features provided by the Human-Machine Interface (HMI). In addition, the limited technical skills of owner technicians require frequent interventions by manufacturer technicians even for minor reconfigurations;
- *distributed deployment*: typically, each owner (e.g., ice cream vendor) uses a limited number of machines and, in any case, machines are loosely connected, i.e., there is no need to coordinate them in a strict way as it happens in production/assembly line environments.

The smart appliance scenario presents vendors with interesting opportunities. In fact, by implementing remote machine monitoring and control infrastructures, vendors could adopt predictive maintenance strategies that can automatically detect degradations likely to lead to malfunctions in the future, e.g., by forecasting the remaining useful life of rotating gears and bearings or by detecting a deteriorating efficiency of refrigerating systems. This would allow vendors to optimize the scheduling of on-site assistance interventions according to multiple objectives. For instance, using machine components almost up to their breaking point enables to minimize repair costs and machine downtimes to preserve customer revenue stream. Considering the specific case of Carpigiani's ice cream machines, Teorema allows: to detect anomalous decreases in the efficiency of the refrigeration systems, usually due to leaks of the coolant gas or degradation of the thermal paste; to monitor degradations of the beater system, usually due to mechanical stress; and to schedule interventions in a cost-effective manner, at the same time maximizing the utilization of experienced technicians and minimizing machines downtimes. As a consequence, vendors can considerably cut down their after-sale assistance costs and even adopt novel business strategies, including low pricing for after-sales assistance contracts and pay-per-use business models (towards servitization).

Furthermore, we claim that smart appliances allow owners to move towards more complex, innovative, and challenging smart value chain scenarios. The main objective is to consider products throughout their whole life, starting before production, e.g., considering design/engineering processes and component provisioning, up to after-sale services, considering added value services, such as e-Maintenance, and even decommissioning.

III. Related Works

The current trend towards the integration of ICT in the manufacturing industry is clearly demonstrated by many recent research papers focusing on this topic [1, 6-8]. [9] outlines most important issues to address in smart industry scenarios, including also the management of supply-chains based on data. [3] presents several economic opportunities that smart manufacturing can enable, ranging from predictive maintenance to process improvement and the offering of new business models based on per-use fees. For instance, servitization is a business model in which smart appliances are offered in real "pay per use" mode, avoiding advance payments and eliminating the consumption calculation because the amount of each transaction is calculated in real time.

So far, industrial and academic researcher in the area has mainly focused on IoT solutions applied on the factory. For instance, by considering recent notable examples, [10] presents an agent-based solution to automate the management of the shop floor in a distributed way, while [11] proposes Ubiquitous Manufacturing to maximize the production capacity. The adoption of big data (and, in particular, neural network techniques in the sense of deep learning) has been proposed to enable active preventive maintenance solutions [12]. Instead, [13] focuses on challenges to provide a reliable and time-sensitive communication technologies, considering both intra-factory wired (e.g., for smart manufacturing) and remote wireless (e.g., for smart appliances) links.

Less attention, instead, has been devoted to more distributed real world industrial use cases, such as the large-scale worldwide deployed scenario targeted by Teorema. For instance, [14] focuses on condition-based maintenance of railways, by adopting IoT to remotely monitor the state of equipment and more efficiently deem if on-site personnel maintenance actions are required while [15] focuses on the evaluation of railroad tracks to optimize maintenance scheduling. [16] adopts e-Maintenance to remotely monitor the state of smart bulldozers and dynamically assess their performance degradation exploiting an adaptive learning technique. [17] presents how monitoring of machine and equipment conditions in mine environments is currently adopted as a key element to enable preventative maintenance, thus reducing downtime and increasing machine lifetime. [18] exploits Augmented Reality (AR) to support an unskilled technician in the maintenance procedure by remotely connecting a skilled operator in a control room. [19] goes a step forward, presenting a general architecture for enabling industrial tele-maintenance comprising both supervision and remote maintenance of distributed equipment, applied to the notable use case of a large subway environment. Finally, [20] presents a more general-purpose condition-based maintenance solution applied to Automatic Test Equipment (ATE) to minimize the device testing cost. While it presents a solution that can be applied by interacting with devices providing self-diagnostic tests, its adoption seems to be limited to a testing environment, thus not designed for and validate in a distributed worldwide use case.

All above literature contributions demonstrate the academic and industrial interest in the adoption of ICT to connect, monitor, and control remote devices to provide novel services. However, so far there is little evidence on how this vision can be adopted in real world, large scale, global wide use cases comprising thousands of appliances deployed worldwide, especially considering recent standardization efforts in this lively area. To this purpose, the paper reports about the design, development, and exploitation of the Teorema project for smart ice cream machine management as a notable use case along this new generation of solutions toward wider standard-enabled interoperability.

IV. RAMI 4.0 Model within Smart Appliance and Value Chain Scenarios

The Industry 4.0 smart factory scenario is currently under great consideration from big companies as well as central/regional governments pushed by the expectation of a ground-breaking change of perspective in the manufacturing sector, the delivery of new services, the provisioning of new business opportunities, and the creation of new employment. We foresee a twofold evolution. On the one hand, the accelerating trend towards ICT-based automation could limit the employment of operational personnel in production lines. On the other hand, it will push for the recruitment of novel professionals with cross-discipline expertise not only in embedded systems and electronic, but also in computer networking and Web technologies.

Apart the impact on smart factory, we claim IoT will significant penetrate also the smart appliance scenario, although there is still no wide agreement on the fact that IoT solutions could achieve every anticipated goal [21]. Let us note that the lack of a standard architecture and a vocabulary to clearly describe proposed and already developed smart appliance solutions greatly limits the capability of inter-enterprise cross-fertilization, already limited by business privacy and competition. In fact, by describing each product and service with a different terminology, in terms of general architecture as well as single components, pioneering enterprises fail at appropriately presenting their achieved results, arising great heterogeneity and delving into fragmentation and disarray in the communication effort.

To push for a coordinated and homogeneous approach toward the smart factory paradigm, standardization groups as well as governments are proposing new unifying architectures and terminologies considering business as well as technological issues [22]. The main goal is to provide a common playground to better identify main critical aspects and easily compare different solutions. In this context, RAMI 4.0 has recently emerged as the most promising model [4]. Compared to other emerging standards that mainly focus on how smart appliances (and related data) are managed, such as the Industrial Internet Reference Architecture (IIRA) [23], RAMI 4.0 is more suitable to model the wider smart value chain scenario also properly handling the whole life cycle development, deployment, and maintenance of smart appliances. In fact, RAMI 4.0 was natively conceived to tackle complex Industry 4.0 scenarios: it considers the management of remote devices only as one of its sub-directions, by providing additional and relevant considerations and extending it along the so-called *Life Cycle and Value Stream* and the *Hierarchy* directions. The final model is a 3-dimensional reference architecture consisting of:

- *Layers*: this vertical dimension providing a traditional segmentation of the IT architecture, by adopting a layered design to facilitate the development of novel solutions. This dimension starts from *Assets* (physical objects) and its *Integration* layers to digitalize them while the upper *Communication* layer provides their remote access. Then, the *Information* layer gathers and manage data to feed the *Functional* layer offering high-level capabilities to monitor/control underlying physical objects, and finally the top-level *Business* layer presents processes related to the whole organizations;
- *Hierarchy Levels*: this horizontal dimension provides per-component functional descriptions depicting how (smart)

product lifecycle can interact in a cross-layer way with any other component typical of the factory. That ranges from field and control devices to stations, work centers, and the enterprise as a whole. The ultimate goal is to maximize the flexibility of the system extending the factory environment to the external world;

- *Life Cycle and Value Stream*: this horizontal dimension focuses on whole products, starting from their design and development to their actual production, deployment, and maintenance. It clearly identifies and differentiates the Type phase, to develop and maintain a new product, and the Instance phase, to produce and maintain single instances of the product itself once it has been fully designed and developed, thus also comprising e-Maintenance processes. This perspective is very significant for the whole production of a small lot of products. It is worth noting that the Life Cycle and Value Stream of different actors can interact and interleave with one another. For example, the output of the Instance phase of a vendor selling machine components may represent the input of the Type phase of an enterprise currently designing and developing a novel machine. This approach allows to better characterize the value chain, making clearer the many and different interactions among the subsequent phases of the life of a product within an enterprise, thus improving its management. Furthermore, it underlines dependencies on external enterprises, e.g., highlighting potentially critical aspects such as a strong dependence on a given product of a seller.

In conclusion, RAMI 4.0 includes the basic definitions and building blocks that allow to model the smart value chain scenario, based on the Life Cycle and Value Stream. It allows enterprises to better identify and delineate the many aspects involving the design, development, and deployment of smart appliances, making easier their description and full comprehension among (internal and external) personnel in charge of interacting with them. At the same time, let us note that most of RAMI 4.0 use cases focuses on smart factory and in general on maintenance of large size and expensive smart products. Instead, we believe that there is the need of applying these standards also in smart appliance scenarios and to manage them along their whole lifecycle, as we propose in the following sections.

V. CARPIGIANI SMART ICE CREAM MAKING SOLUTION

Carpigiani is one of the world leading industries in the market of ice cream making machines: it sells in 110 countries all over the world, being its machines installed in ice cream shops and restaurants. Machines operate without any on-site technical support and, despite the high build quality, they incur into non-negligible maintenance costs during their long (10 to 20 years) expected lifetime, because of the high duty operations they are subjected to.

Carpigiani embraced the Industry 4.0 revolution pervasively, adhering to the manufacturing philosophy discussed in the first part of this paper. The Teorema solution integrates ice cream machines in a smart value chain that involves many different stakeholders, ranging from ice cream shop owners and workers to final customers, positioning Carpigiani in the leading edge of the smart appliance trend [1]. Teorema includes five primary smart services detailed in the following.

The *safety* service represents a fundamental aid for ice cream shop owners. By monitoring and recording the temperatures of ice cream produced by each machine, and providing detailed and (soft) real-time reporting, Teorema allows to improve and certify the safety of ice cream consumers and permits an early detection of issues related to food supply. In this manner, machine owners, namely, ice cream makers, can certify that ice cream production processes did not “spoil the cold chain” and did instead follow the strict Hazard Analysis and Critical Control Points (HACCP) food safety standards.

The *efficiency optimization* service automatically monitors the usage patterns of ice cream making machines and suggests more efficient processes. For instance, at fixed time periods it is required to completely empty the machine to perform a sanitization cycle, throwing away remaining ice cream ingredients. When the operator needs to refill the machine, Teorema can report the exact amount of ingredients required to serve ice cream until the next machine sanitization cycle, thus minimizing food waste. Note that the machine advices the operator about how much ingredients to add also based on recent ice cream consumption trends and weather forecast (e.g., in case of rain ice cream consumption typically decreases).

The *energy optimization* service analyzes all the details of the production needs of multiple ice cream machines in the same shop and can advise how to save energy. It will always recommend the most efficient use of the machines, based on the actual business needs. For instance, it is possible to limit peak energy consumption by automatically planning ice cream processing tasks (pasteurization cycles) when other appliances in the same ice cream shop are in standby. The system indicates if a single machine is ready to produce or has to be switched to conservation according to the state of other machines and it keeps track of daily energy consumption. Experiences with early adoptions of the energy optimization service, as well as extensive and accurate simulations of ice cream machine operations in a wide range of realistic scenarios, indicate that it might be capable of reducing peak energy consumption of a typical ice cream shop up to 20%.

The *smart maintenance* service allows Carpigiani (manufacturer) technicians to actuate predictive maintenance strategies via a deep knowledge of machines operating conditions on the field. Teorema enables to remotely monitor the synoptic state of ice cream machines and allows real-time visualization and analysis of collected data via a Web interface. The Carpigiani e-Maintenance service aims at detecting faulty components by exploiting data provided by the connected product to automatically generate alarms reports describing anomalous conditions or the successful completion of processes such as pasteurization and operational logs (*"events"* in Teorema terminology) to monitor the current state of the machines. Remote maintenance functions allow to significantly reduce after-sale assistance costs and fix time. In fact, remotely reconfiguring working parameters (or even upgrading the firmware) is often a very effective way to fix issues exhibited by ice cream machines or to extend their lifespan.

For instance, reducing the rotation velocity of the beater component or increasing the times for the pasteurization process allows a smart planning of on-site assistance interventions which minimizes their costs. That not only results in lower operational costs for customers (machine owners), but also allows to explore new service-oriented business models better aligned to customer needs. Moreover, the integrated Carpigiani warehouse enables prompt verification about the availability of the required spare component and possibly promptly reorders via integration with supplier ERP to ensure the prompt retrieval and delivery of the spare part. At this point the ice cream machine specialized technician can schedule the on-site intervention to fix the machine.

Business support service includes a business dashboard that allows customers to check the state of their machines and control the profitability of their ice cream shops or restaurants. For customers running several shops, Teorema allows location-aware comparisons between the related business performance metrics, to assess if at a specific shop any machine mismanagement practice is lowering profitability, e.g., delays in machine cleaning cause unnecessary downtimes. In addition, the increased efficiency in after-sales assistance services brought by Teorema allowed to start offering pay-per-use contracts, in which customers lease (remotely controlled) ice cream machines instead of purchasing them.

Finally, let us also note that Teorema allowed Carpigiani to switch to a mass customization manufacturing practice. While Carpigiani was never a mass production company, with the adoption of Teorema, the firm has started to ship ice cream machines only with a basic stock software, and to install customer-specific software at the moment the machines are installed in customer premises. The adoption of Teorema-enabled mass customization policies achieved a significant reduction in delivery times and in customization costs, paving the way to new services such as fine-grained and on-demand tuning of ice cream making processes implemented by machines, facilitating customers in developing their own ice cream recipes.

Let us conclude this section drawing some first lessons learned based on the Carpigiani experience. First and most important, the adoption of Industry 4.0 principles in relatively cheap and small machines can enhance smart scenarios by enriching new services with a plethora of information traditionally available only to the specific department they were generated in a silos-based way. Indeed, horizontal and vertical integration, as suggested by RAMI 4.0, are overwhelmingly important. Adopting horizontal inter-area integration, Industry 4.0 can take full advantage of every information smart appliances produce, creating new value by pushing towards cross-fertilization of different departments. Through vertical integration, instead, Industry 4.0 can feed different organization levels with information generated by other levels, enabling improved top-level manager decision making according to up-to-date production information and incoming orders. For instance, if a production line in a shop floor is currently underperforming compared with its target, operational managers can be promptly informed to allow investigating possible issues. As a consequence, it is possible to detect (and take proper countermeasures) in case the productivity is lower than expected as soon as an issue may arise (thus not waiting for weekly reports provided by production line supervisors) or more easily reschedule machine production in case it is required to fulfill an unforeseen high priority order.

However, to fully enable and adopt the smart value chain scenario, manufacturers should more carefully consider following primary aspects related to the Industry 4.0:

- *integration with ICT of traditional production mechanisms/activities/tools* to ease smart appliance deployment, by adopting Web-based and cloud-based architectural solutions, such as persisting of IoT data and processing them in Cloud;
- *joint availability of data generated by machines and by processes involving humans* to integrate data that range from the number of produced items per minute and faults per day to information regarding customers, technicians, and partners stored in traditional CRM/ERP tools;
- *autonomous management behavior* to enable machines take proper decisions to achieve greater flexibility, efficiency, and resource-saving, such as smart appliances leveraging, e.g., expert systems to autonomous reconfigure their working parameters to enter a more conservative, albeit less efficient, operating mode that extends machine remaining useful life in case of misbehavior of (part of) involved machines;
- *adoption of business intelligence and machine learning* to properly exploit the great amount of generated and persisted data to provide novel insights related to products and processes, e.g., correlating weather forecasts with daily ice cream consumptions.

VI. Teorema: Architecture and Implementation

Teorema is the comprehensive and integrated (hardware and software) platform at the heart of Carpigiani smart appliance solution for ice cream making machines. As illustrated in Fig. 1, Teorema has a distributed architecture made of several software components, running either on the ice cream machines or in Carpigiani hybrid cloud environment (with components running on either a private cloud or on Amazon AWS cloud, depending on customer preferences). Teorema is based on three main components: *Machine Remote Control* (MRC) behaving as a client and running on a single board computer installed at ice cream machines, and two server-side components, namely, *Machine Managemen*t (MM) and *Machine Web Interface* (MWI) acting, respectively, as the entry point for information dispatching and as the multi-role graphical interface. Additional information about Teorema functions can be retrieved from the dedicated Carpigiani Services Web site[2], with the company brochure and a video[3] describing the offered smart system. In addition, a dedicated mobile app is available on Google Play[4] and Apple App Store[5] with credentials for a predefined demonstration account available

[2] https://service.carpigiani.com/index.html
[3] https://vimeo.com/261106137
[4] https://play.google.com/store/apps/details?id=com.carpigiani.teorema
[5] https://itunes.apple.com/us/app/teorema/id592757378?mt=8

together with a video[6].

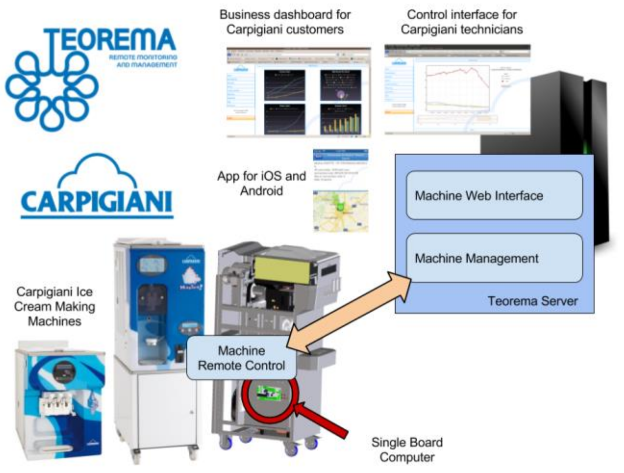

Fig. 1. The Teorema smart appliance solution.

A. Teorema and RAMI 4.0

Before thoroughly describing the architecture of the Teorema solution, this section compares its high-level architecture with some notable aspects of RAMI 4.0, to evaluate the suitability of RAMI 4.0 to the smart appliances scenario while validating the design and architectural choices made in the Teorema platform.

Let us note that the design and development of Teorema started in 2007, well before the RAMI 4.0 reference architectures were introduced, and also before IoT and Industry 4.0 related concepts and tools became mainstream in the industrial sector. However, by anticipating the industrial state-of-the-art, Teorema presents many interesting similarities with the models of almost one decade afterward.

First of all, Teorema nicely fits the RAMI 4.0 Layers vertical dimension by adopting an architecture that neatly separates: Assets, i.e., ice cream machine themselves; Integration and Communication, based on cellular enabled off-the-shelf boards (additional details in Section V-B); Information and Functional, by storing gathered data in relational databases and allowing to access them to perform advanced data processing (additional details in Section VI); and Business, providing differentiated high-level information to several stakeholders, e.g. technical details of running machines to R&D engineers, smart maintenance services to service providers, and business support services to ice cream shop owners to better exploit their machines and investigate their daily usage.

Moreover, the relevance of RAMI 4.0 Life Cycle and Value Stream direction is demonstrated by the fact that Carpigiani exploits RAMI 4.0 Type/Instance approach. In fact, Teorema allows to monitor new machine models starting from early-stage prototype development to the deployment of pre-production machines on customer premises and to final design and production, validating each machine component and functionality during the entire product design and production cycle. This enables to improve, if needed, the design of ice cream machine by early detecting eventual malfunctions during on-the-field operations, tracking the root causes, and fixing them. In addition, in the Instance phase the Teorema project has enabled many smart services, from e-Maintenance and smart after-sale scenarios to per-machine customization and usage monitoring. For instance, Carpigiani leverages Teorema to provide customized software versions with per-machine granularity that implement modified cooling processes allowing customers to prepare special ice cream recipes.

Finally, Carpigiani smart appliances follow only partially the RAMI 4.0 Hierarchy Levels direction in relation to communication. Ice cream machines deployed outside the factory environment (actually enlarging factory virtual borders) are connected to the Carpigiani factory through MRC/MM interactions, such as RAMI 4.0 smart appliances. However, while RAMI 4.0 adopts a cross-layer approach allowing (smart) appliances to interact with any smart factory component, Teorema MM and MWI components act as intermediary between ice cream machines and other Carpigiani enterprise-wide tools (such as CRM and ERP). In fact, while we recognize that a cross-layer approach increases the flexibility of the adopted solution, thus potentially enabling additional service opportunities, we believe that its costs in terms of development and management complexity in the smart appliance scenario may overcome its benefits. Hence, based on our experience, we propose a tailored approach specifically fitting requirements stemming from the target application scenario.

B. Teorema implementation

The machine-installed software, as in Fig. 2, consists of two event-driven, concurrent, and continuously coordinating components running on top of an ARM-based Single Board Computer (SBC). The Supervisor application deals with high frequency and low-level communications with the main hardware components of the machine, allowing the Unified Teorema Interface (UTI) to focus on higher level functions with a hardware agnostic approach. Supervisor is also in charge of managing software upgrades, of enforcing operational safety protocols at all times, and of managing the configuration of machine working parameters. UTI instead provides a state-of-the-art HMI that integrates 3 important modules: Process Management, Energy Monitoring, and Remote Control. Process Management performs a comprehensive control of the ice cream managing process, implementing custom recipe execution, enforcing food safety protocols, and monitoring and optimizing the process efficiency. Energy Monitoring measures energy consumption, builds a model of machine usage and suggests possible optimizations. Remote Control, provides remote monitoring and control functions and can optionally work as a standalone component. That makes Teorema easy to retrofit on older machines, by running the Remote Control module on top of a remote monitoring kit connected to the machine's RS-485 diagnostics interface.

Focusing on the server side, we detail main interactions and inner components of MM and MWI in Fig. 3. MM receives maintenance data from ice cream making machines and stores it in a dedicated DBMS; it is also in charge of coordinating software upgrades. Leveraging collected data, MWI consists of six components that provide all the main

[6] https://www.youtube.com/watch?v=6hG7MgOY5uA

functions of the Teorema platform, implemented on top of three core components: Business Logic, Role-Based Authentication Control (RBAC), and CRM/ERP Integration. Configuration Management allows to trigger (or schedule) software updates and working parameter reconfiguration for a single machine or a group of machines, through an easy to use interface. Visualization provides comparative visualization functions for the data collected from the machines, allowing the easy detection of anomalies. Business Dashboard provides an interface to the Teorema platform specifically dedicated to Carpigiani customers, that allows them to monitor the revenue and efficiency of their ice cream making machine and to take action when needed. Reporting provides multi-role fine-grained management functions over either PDF or e-mail. ReST API exports all the main platform functions through a programmable interface, allowing to access them remotely, e.g., via mobile apps.

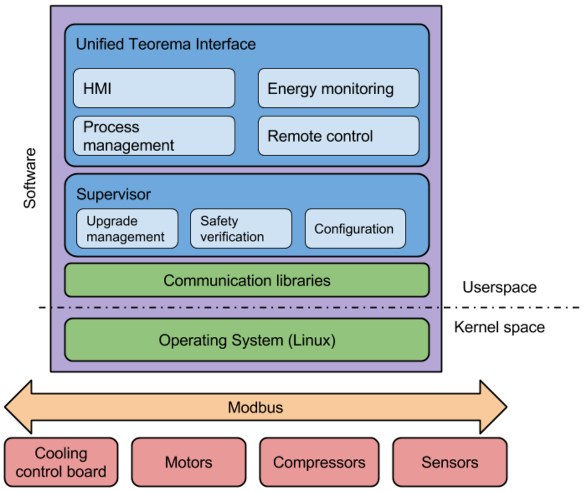

Fig. 2. Software architecture of Carpigiani machines.

Finally, MWI includes Analytics that is arguably the most important component in the entire Teorema platform. In fact, it is in charge of processing the data collected by the ice cream making machines, of aggregating them to build knowledge on machine processes (for instance, the pasteurization treatment), and of building behavioral models for each machine. In addition, Analytics provides both automated failure detection and prediction functions, implemented on top of sophisticated Big Data solutions that execute diagnostics and anomaly detection algorithms in a private Cloud. More specifically, Analytics implements threshold-based (soft) real-time monitoring of the machines' operating conditions using raw data collected from the machines, together with time series analysis, e.g., one nearest neighbor (1-NN) and Dynamic Time Warping (DTW) [24].

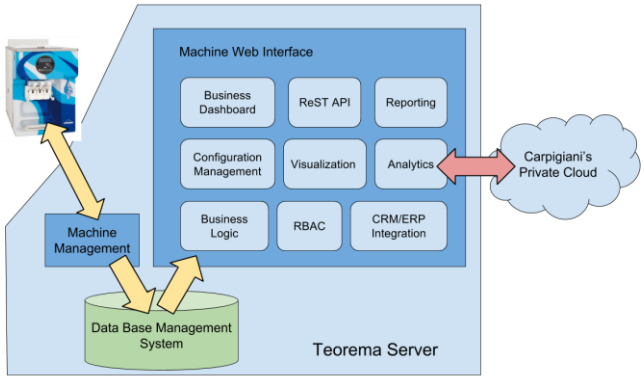

Fig. 3. Architecture of server-side Teorema components.

VII. Teorema at Work

Teorema remote management functions enable to facilitate e-Maintenance operations along two different directions. The first is the prompt detection of *unpredictable failures* to consequent report them to technicians in charge of the maintenance of the machine. In this case machines abruptly present performance degradation and the Teorema solution is exploited to promptly notify it together with technical details to more easily fix issues at the following on-site maintenance. The second, more ambitious, goal is to detect early the inevitable *performance drift* of machines along their lifecycle, forecasting the likelihood of breakdowns and automatically mitigating actions (such as reconfiguring the machine working parameters, or temporarily reducing its performance to increase time-to-failure), so to plan preventive assistance interventions. That is the base for the implementation of *predictive maintenance* practices. In the following we present two notable cases related to the pasteurization process and the beater component.

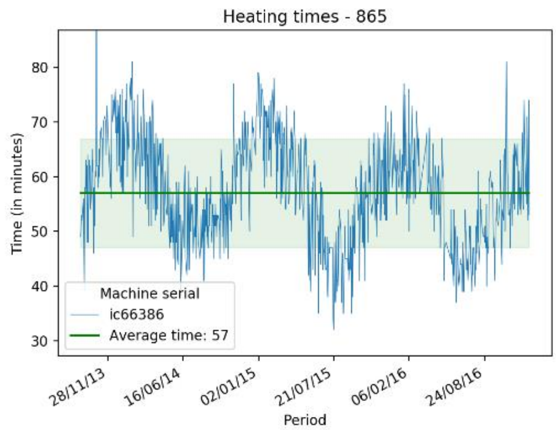

Fig. 4. Heating times of a correctly operating machine, exhibiting a seasonal dependence from external temperature.

The time required to complete the pasteurization process is one of the most useful metric for smart maintenance, exploited for detecting both unpredictable failures and performance drifts. Each machine undergoes a pasteurization treatment consisting of: heating (from 4°C to 65°C), pause (about 30 minutes at 65°C), and cooling (from 65°C to 4°C). The time required for the heating phase may vary in relation to the mixture receipt and the environment temperature, with seasonal variations that should be considered as a regular behavior (see Fig. 4).

Variations that sharply deviate from the regular seasonal pattern indicate an abrupt failure, maybe because the efficiency of the heater is degraded or the machine is too close to an air conditioner slowing down the heating phase. For instance, Fig. 5 shows the sequence of times required for the heating phase of the pasteurization process reported by a specific machine. The impromptu and unpredictable variations at the right edge of the plot indicate a severe breakdown that was promptly detected by Teorema and reported to the technicians in charge of machine maintenance.

In the planned maintenance domain, the comparison between different machine can provide core indicators: pattern deviations due to performance drifts are often less visible and require to consider longer time periods to be detected. For instance, Fig. 6 shows that the time required for the entire pasteurization process in a specific machine slowly but constantly increases, of about 13% in 6 months. In this case, Teorema detects early the slow degradation of the machine by cross correlating its maintenance data with the other data collected from machines of the same type and in similar operating conditions (in particular with regards to installation location and lifecycle).

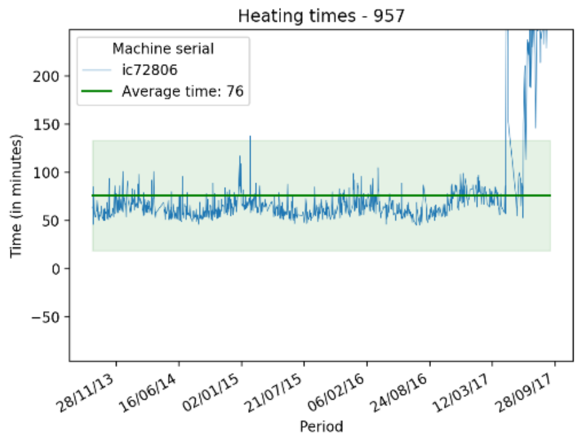

Fig. 5. Heating times of a malfunctioning machine, that had an impromptu and unpredictable breakdown.

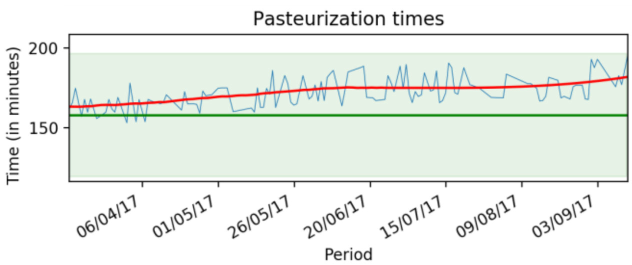

Fig. 6. Pasteurization times of a machine exhibiting a mild performance drift.

Another notable example of the exploitation of Teorema has been the study of the ratio between the number of hours the beater motor worked and the number of produced cones is an effective metric to evaluate the health of the beater component. The beater is in charge of mixing the ingredients during ice cream production and represents one of the most critical components in an ice cream machine, as its blades are subject to considerable wear and tear over time. Before delving into details, let us note that while in general a lower gradient corresponds to a higher energy efficiency, different machines depending on their deployment context present different trends because they operate in very different conditions and operating environments. For instance, ice cream production in machines installed in warmer climate might require more energy compared to those operating in colder ones. Fig. 7 presents the values of that ratio for 3 notable use cases (each curve represents a different ice cream machine).

Let us start from the blue and red curves (respectively, the upper and lower ones in Fig. 7) that correspond to healthy machines (namely, machine #2225 and #1098) that, however, exhibited an abrupt problem and started consuming too much energy with respect to the current number of produced cones, respectively, an issue suddenly fixed at the installation time for the blue one, and a problem due to a sudden change in the operating conditions over 150000 cones for the red one. The green curve (the one in the middle), instead, shows a continuous and slight increase that corresponds to a machine exhibiting a mild performance drift (#1216) that indicates either the degradation of the beater motor efficiency or some misuse of the ice cream machine by the operator.

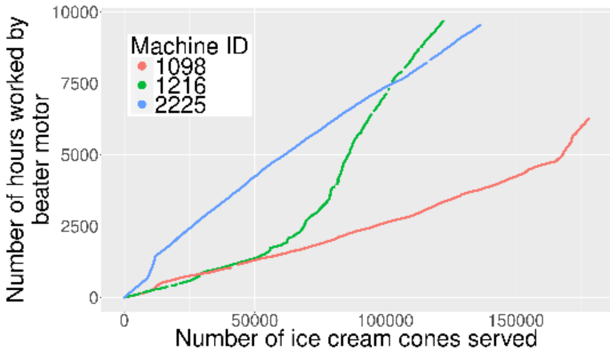

Fig. 7. Ratio between hours worked by the beater motor and number of ice cream cones served in 3 different machines: one operating correctly (#2225), one exhibiting a performance drift (#1216), and one exhibiting an abrupt performance degradation (#1098).

From an analysis of the number of hours the beater motor worked and the number of produced cones ratio (Fig. 7), we detected that in a few ice cream machines, operating in particularly challenging environments, the beater was subjected to unexpected levels of mechanical stress. Based on those data, Carpigiani redesigned the beater component, strengthening the most critical parts. Feedbacks of this kind on the design of machine components allow on-the-field detection of structural problems leading to significant cost savings and enhanced customer satisfactions.

VIII. Conclusions and Future Works

The adoption of the presented solution in 2008 marked the beginning of a new era for Carpigiani: as an early manufacturer adopter of Industry 4.0 practices, it enabled the creation of a new IT-specific group to address the challenges of smart appliance scenarios and to anticipate solutions.

First, the much-improved efficiency in after sales assistance permitted to experiment new business models, including servitization. In addition, the data collected by Teorema about the behavior of machines operating on-the-field created an incredibly valuable feedback to the design of the next generation of ice cream machines. Finally, the adoption of IT industry best practices enabled also other innovative strategies, such as extensive usage of open source COTS and greater attention to security issues.

Future ice cream making machines are likely to be even more connected, so that the coordination with other co-located machines can really create *smart kitchen* environments that suggest and open new service perspectives.

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