Holonic Condition Monitoring and Fault-Recovery System for Sustainable Manufacturing Enterprises

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Abstract. Relatively new technologies such as sensor networks and automated identification, and increased computational power available through distributed computing offer the advantage of real-time monitoring of manufacturing resources and production orders. This work integrates the distributed manufacturing concept, largely used previously in constructs such as agent-based and holonic manufacturing systems with the new sensor network and distributed computing technologies embedded within the manufacturing system for condition monitoring and fault-recovery purposes. Failure, mode, and effects analysis method is also considered in the model. Through this integration the simulated operations of the proposed manufacturing enterprise model receive more visibility, flexibility, and agility and, ultimately, provide a sustainable enterprise model able to address in real-time the uncertainties of the manufacturing environment for the entire lifetime of the manufactured products, as well as the lifecycle of the manufacturing equipment.

Keywords: real-time monitoring, distributed manufacturing, agent-based and holonic modelling and simulation, sustainable enterprise systems.

1 Introduction

The fierce global competition that manufacturing industry is facing in the last decade asks for new solutions to complete all orders in the shortest amount of time, with the lowest budget, and while maintain a high level of quality. Requirements such as strict deadlines, keeping low inventories, uncertain demand, standardization of manufacturing processes, products diversity, increased production control, and resource limitation changed the operational mode of manufacturing systems, with increased challenges for optimization of the operations within the manufacturing system and across the supply chain. Classic problems related to manufacturing optimization, such as production planning, job scheduling, and assignment of resources in the presence of different uncertain variables such as stochastic and diverse demand and resource unavailability (e.g., machine breakdowns) cannot be addressed efficiently anymore

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using analytical and mathematical models. Enhancing the manufacturing environment for more visibility and better control of the production processes by integrating new technologies presents opportunities for the manufacturing domain.

Distributed intelligent manufacturing literature abounds of multiple types of agent-based and holonic frameworks and constructs, which present the advantages as well as disadvantages of adopting such an operational mode. Though for large enterprise systems the proposed models outperform the classical centralized manufacturing schemes, the real-world has yet to see a significant penetration of such systems. This reduced adoption of distributed agent-based and holonic systems in manufacturing operations is a result of varied reasons, which mostly deal with the cost of replacing current shop-floor and control process equipment. Sensor networks are already used for condition monitoring for a large spectrum of applications. Individual sensors provide feedback control in manufacturing applications, by monitoring parameters such as tool temperature and vibration levels, as well as machine-tool monitoring. Undetected wear of tooling and of the machine tools leads to low surface quality, many times resulting in scrapping the raw material. Any potential safety issues can also be monitored by individual sensors deployed on machine tools.

This work continues the research started by the authors and reported in [1]. It complements the distributed intelligent manufacturing concept with relatively new technologies, such as sensor networks and distributed computing, in an attempt to add more value to the entire distributed manufacturing enterprise concept and raise the attention about its potential benefits in uncertain environments. A network of wireless sensors is proposed to be embedded within the physical resources of the manufacturing enterprise. Just as an agent-based or holonic manufacturing system, the sensor network collects, analyses data, and exchanges information with other entities in the system, using computational agent-based and holonic distributed schemes. The performance of the proposed holonic model, enhanced with preventive maintenance capabilities, featuring a real-time condition monitoring and fault-recovery mechanism, is compared with that of a holonic system that uses the traditional corrective maintenance approach. As a further enhancement of the preventive maintenance capabilities, the proposed real-time condition monitoring and fault-recovery mechanism also includes a Failure, Mode, and Effects Analysis (FMEA) module that provides data related to the likelihood and severity of faults.

2 Literature Review

Pereira and Carro [2] propose an agent-based manufacturing systems consisting of a set of autonomous, intelligent, and goal oriented units that can benefit from large-scale distributed real-time embedded systems. One of the systems considered is a wireless sensors network, where the sensor nodes cooperate effectively to reach their global objective by using coordinated decision-making. Flexible and agile manufacturing, which provide the ability to react to expected or unexpected changes and uncertainties is addressed by Stecke [3]. The author considers that flexible manufacturing problems are not restricted to scheduling, planning and design problems only, but they also include the control problems associated with the continuous monitoring of systems and tracking of production orders which must meet specified requirements and due dates.

The holonic manufacturing systems concept presented by van Brussel *et al.* [4] states that its goal is to obtain in manufacturing the benefits that holonic organization provides to living organisms and societies. Holonic systems consist of a set of entities, called holons, which are strongly connected with the physical level devices [5-7]. The holons are viewed as building blocks of the entire system architecture, consisting of an information processing part and a physical processing part. The holons execute all sorts of manufacturing operations ranging from material transformation processes, assembly processes, loading, unloading, and transportation processes, storing and inventory build-up processes, or just information processing related to the physical entities part of the system. A holon is characterized by the following two mandatory characteristics [4]:

- *Autonomy*, defined as the capability to make decisions and execute the selected plans; and,
- *Cooperation*, defined as the relationship with other holons in the system to develop mutual plans and execute them with respect to basic rules that limits their autonomy in order to achieve a goal or mutual objectives.

The literature review clearly identified these characteristics, on the one hand, as being of utmost importance for the operation of holonic manufacturing systems. On the other hand, the operation of holonic manufacturing systems, and of any other manufacturing systems for that matter, cannot be sustained without monitoring and control of the manufacturing operations. In the case of a holonic system, which attempts to provide real-time routing and scheduling of production orders and resources, the manufacturing and control system need to provide the information about the operational status of both production and resources and make it available in real-time for the decision-making process. Several frameworks that consider the implementation of a "real-time monitoring component" within the architecture of advanced manufacturing systems are proposed in the literature. For example, in one of the surveyed works, Zhang *et al.* [8], consider a real-time distributed control system composed of two components. The first component, named Execution Control, is responsible for planning for reconfiguration, fault monitoring and fault detection, while the second component, named Control Execution, is responsible for the basic monitoring and alerts, and for the handling of low-level fault recovery procedures. Koomsap *et al.* [9] reports a significant improvement in performance for distributed manufacturing environments when making process control decisions in conjunction with condition monitoring and machine maintenance decisions. One way to realize this combined decision making process is to link process planning and optimization systems with shop-floor control decision processes (Shaikh and Prabhu [10]).

One of the potential solutions which ensures real-time monitoring for large-scale manufacturing systems is the use of wireless sensor networks. These sensor networks have the required capabilities of sensing, computing and communication of data in real-time. Pereira and Carro [2] mention the use of data provided by sensors and computerized components embedded within the manufacturing resources and other equipment. The data can be used as the main input for implementing intelligent maintenance systems, since the manufacturing resources undergo the process of degradation before their failure, thus the data provided by the deployed sensors can be used for health estimation and failure prediction. The advantages of using sensor networks and distributed computational capabilities for process manufacturing and control are summarized in the work of Shaikh and Prabhu [10], as follows:

- Extend existing manufacturing and process control systems reliably;
- Improve asset management by continuous monitoring of critical equipment;
- Help identify inefficient operation or poorly performing equipment;
- Help automate data acquisition to reduce user intervention; and,
- Provide detailed data to improve preventive maintenance programs.

The review of the literature identified a few papers that consider the Failure, Mode, and Effects Analysis technique in conjunction with distributed control architectures [11-13]. For example, Enright *et al.* [11] provide a comprehensive review and devise an optimal FMEA solution for electronics manufacturing, while Lopez *et al.* [12] adapted the FMEA methodology for failure diagnosis for distributed architectures.

3 Holonic System Model without Condition Monitoring

Building on the holonic architecture described in previous works by Babiceanu *et al.* [5-7] consisting of five types of holons (Order Holon, three Resource Holons, and a Global Scheduler Holon), Babiceanu and Tudoreanu [15] transformed an initial passive system component (*System Monitoring and Database Holon*) into an active holon element. Furthermore, the authors added another component, the *Monitoring System Holon*, which includes a series of wireless sensor networks distributed across the manufacturing enterprise, for the purpose of achieving real-time monitoring and recovery from faults, as follows:

- *System Monitoring and Database Holon*, responsible for monitoring the jobs in the system and availability of resources; and,
- *Monitoring System Holon*, responsible for the preventive and corrective maintenance procedures within the manufacturing system, which include condition monitoring, fault diagnosis, and recovery processes.

The capabilities of these two constructs are further defined and refined in this current work for the proposed holonic system. The new holonic system architecture for condition monitoring and fault recovery, viewed from the enterprise level, is depicted in Fig. 1. The architecture was obtained using a Systems Modeling Language (SysML^{TM}) Block Definition Diagram. The proposed holonic system model consists of a manufacturing plant that, initially, does not include the infrastructure for real-time monitoring of manufacturing resources and processes. Specifically, the proposed manufacturing system model is composed of the holonic entities listed next.

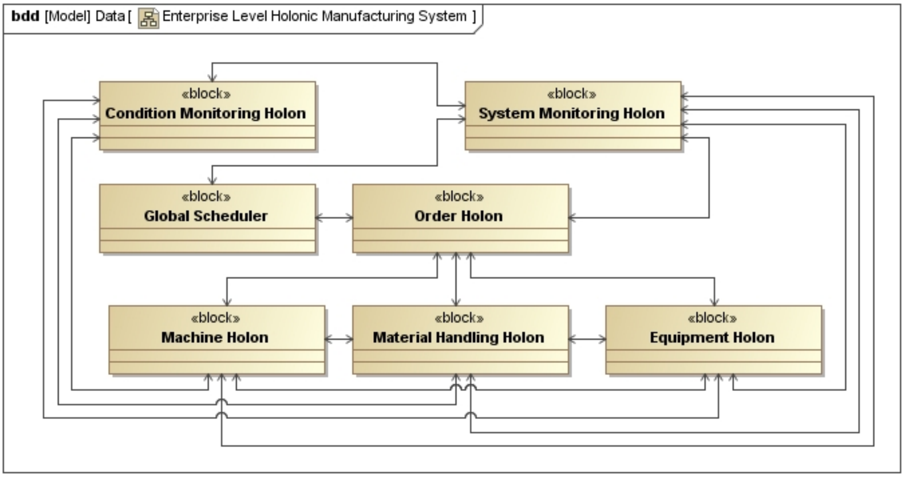

Fig. 1. Holonic enterprise architecture for condition monitoring and recovery

- *Order Holon*, which includes the data regarding the new jobs that enter the system; the *Order Holon* is responsible for scheduling the jobs to the available resources;
- *Resource Holons*, which include all the *Machine*, *Material Handling*, and any other *Equipment*, including storage equipment, such as Automated Storage and Retrieval Systems (AS/RS), and recycling capabilities, that are part of the manufacturing system; the *Resource Holon* is responsible for adding value to the orders processed within the system, and storing the finished parts; and,
- *System Monitoring Holon*, represented by the corresponding holonic instances of the *Purchasing*, *Quality Control*, *Maintenance*, and *Production Control* departments; the *System Monitoring Holon* is responsible for making raw materials available for processing, controlling the quality of the processed orders through a statistical sampling process, performing corrective maintenance of the manufacturing resources, and for any type of production control needs.

The operational instance of the holonic systems, depicted in Fig. 2, was obtained using a SysML™ Activity Diagram. The system, as depicted, will serve its purpose well-enough for a certain time period. However, the system is expected to be effective for the entire lifecycle of the manufacturing resources. The degradation process that machine cells undergo is a continuous process that cannot be noticed in real-time. At some point in time, the machine cells will not be able anymore to provide the expected quality for the orders entering the system. This change in the quality of the throughput will be noticed by the *System Monitoring Holon*, through the *Quality Control* unit, which will conclude that the manufacturing resources (machine cells) entered a degradation process. Once the threshold of statistical sampling process is surpassed, the *Quality Control* unit implements the process described next.

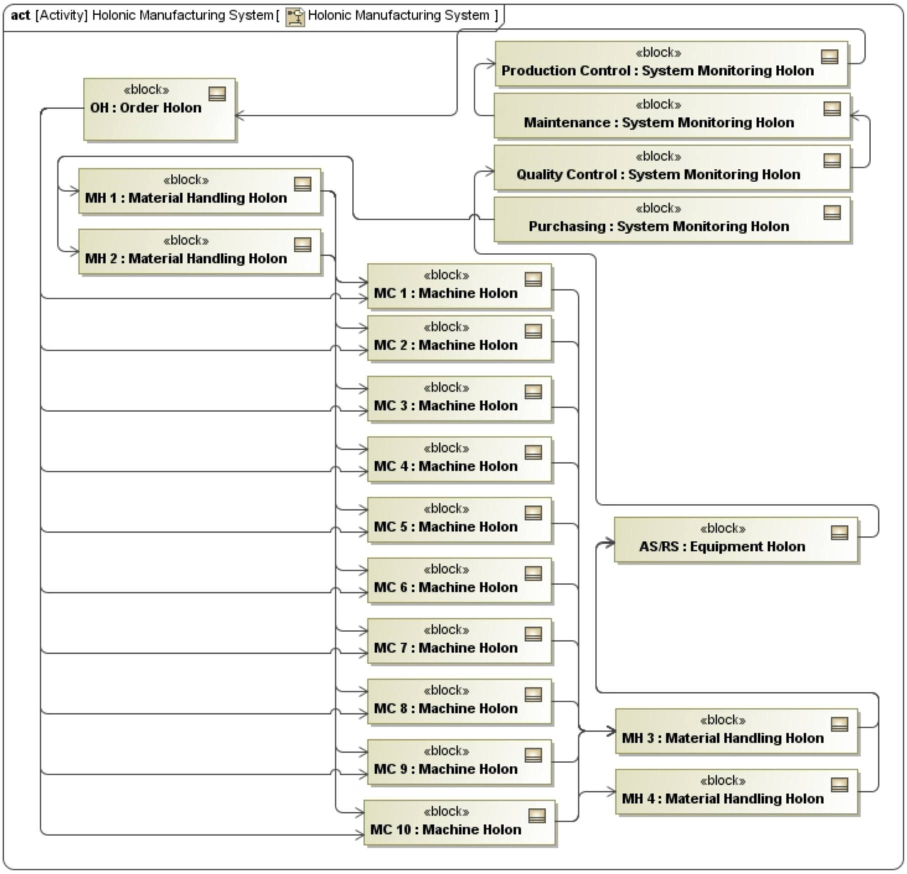

Fig. 2. Operational instance of the holonic manufacturing system

- The identified machine cells of the *Resource Holon* interrupt the execution of the assigned production orders;
- The new jobs corresponding to the rest of the order are re-directed to the *Order Holon* for re-assignment and re-scheduling through holonic allocation among the remaining machine cells;
- The *System Monitoring Holon* starts the fault diagnosis process by collecting data related to the operational variables of the machine cells and the type of faults identified; and,
- Corrective actions are recommended and executed, as a result of the fault diagnosis process.

4 Embedded Condition Monitoring Holonic System Model

4.1 Architecture of the Condition Monitoring Holonic System

The enhanced holonic model, depicted in Fig. 3, is designed to include real-time monitoring and control capabilities and considers the improvement that monitoring of manufacturing resources brings to quality control and responsiveness. The architecture of Fig. 3 was obtained using a SysML™ Activity Diagram.

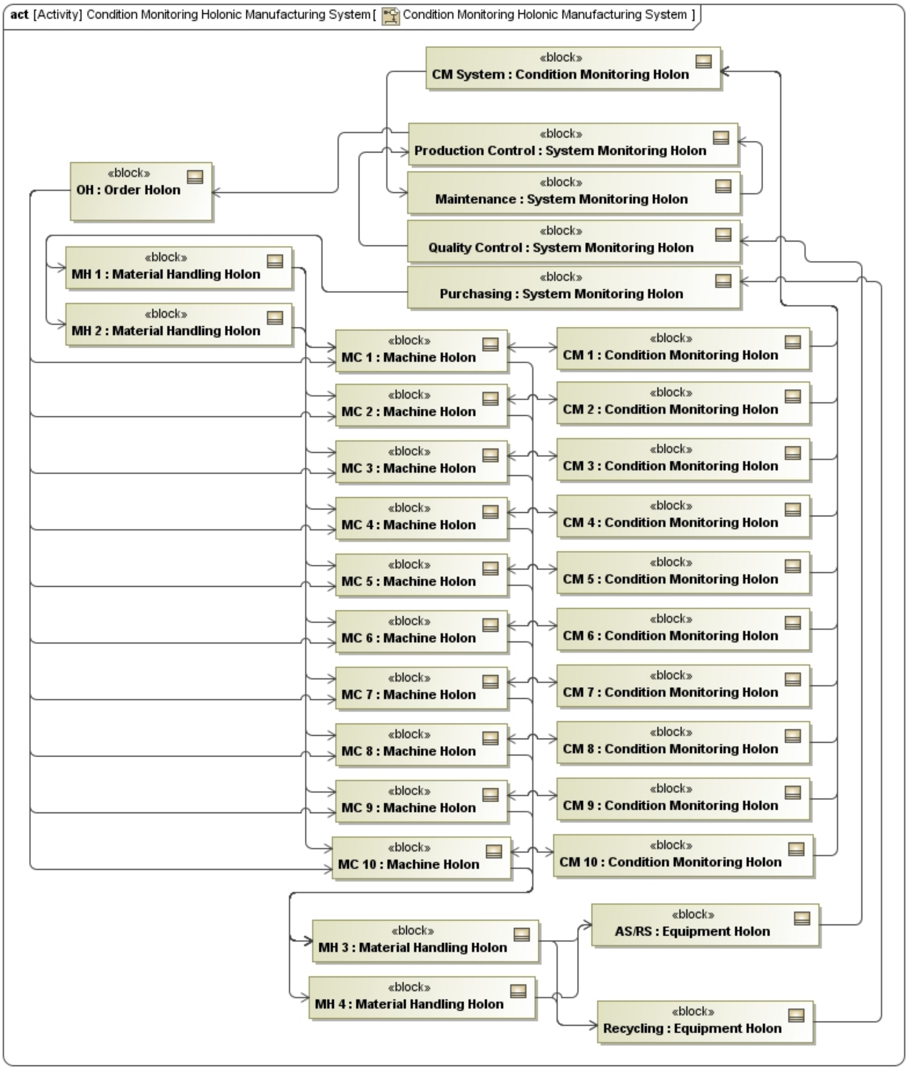

Fig. 3. Operational instance of the condition monitoring holonic manufacturing system

A wireless sensor network is deployed across the holonic manufacturing enterprise to every machine cell to monitor the condition of tooling and of the machines themselves. The holonic manufacturing system with real-time monitoring and control capabilities is composed of the *Order Holon*, *Resource Holons* (i.e., *Machine Holon*, *Material Handling Holon*, *Equipment Holon*), *System Monitoring Holon*, and *Condition Monitoring Holon*, which are described next.

- *Order Holon* is responsible for the real-time resource allocation and job scheduling. These processes are performed based on the holonic autonomy and cooperation processes together with the *Machine* instances of the *Resource Holons*. To accomplish its role efficiently, the *Order Holon* needs real-time data about the status of the machine cells (e.g., availability, reliability). These data are received from the *Production Control* instance of the *System Monitoring Holon*.
- The *Machine Holon* is part of the *Resource Holon* and is responsible for processing the jobs assigned by the *Order Holon*. Each *Machine* instance is monitored by a wireless sensors network (i.e., instance of the *Condition Monitoring Holon*) consisting of a set of sensors collecting data about the machine operational parameters. The data are sent to the *Condition Monitoring Holon* for processing. If the monitored parameters of the *Machine Holon* increase up or decrease below a certain threshold, which is already defined by the process requirements, the *Condition Monitoring Holon* suspends the order assigned to the *Machine Holon* and sets the machine status to unavailable.
- The *Condition Monitoring Holon* is the monitoring unit of the machine cells, and any other pieces of equipment, material handlers, recycling units, and facility units, when sensors are deployed also to these units. When the machine cells are in operational mode, their operational parameters must exhibit values in a defined range depending on the order processing requirements. When one or more of the parameters exhibit values outside the defined range for a specific machine cell, that machine cell entered a degradation process. Consequently, there is a high risk that the produced order is defective.
- The *Material Handling Holon* is responsible for loading/unloading and transporting items from the purchasing department, controlled by the *Purchasing* instance of the System Monitoring Holon to the *Machine Holons* on the shop-floor and from the shop-floor to the equipment controlled by the *AS/RS* and the *Recycling* instances of the *Equipment Holon*.

4.2 Detailed Functionality of the Condition Monitoring Holon

The *Condition Monitoring Holon* is composed of sets of deployed sensors that are measuring and then routing data to their corresponding sink nodes according to a predefined routing protocol, an FMEA module, and a monitoring computational system module. The deployed sensors associated with a *Machine* instance and its computational unit, in this case the sink node, form a deployed instance of the *Condition Monitoring Holon*. The *Condition Monitoring Holon* also exhibits instances associated with the operations on each of the shop-floor of the manufacturing enterprise, and, as mentioned above, *FMEA*, and *Condition Monitoring System* instances. Besides *Machine* instances, the instances associated with the shop-floor operations, could also include *Equipment*, *Material Handling*, *Recycling*, and *Facility* instances. The *FMEA* instance is discussed in the next section.

The *Condition Monitoring System* instances are responsible for processing the data received from the deployed instances of the *Condition Monitoring Holon*. If any of the physical resources of the system enters a degradation process, the *Condition Monitoring Holon* stops all activities performed by that physical resource, changes its status to unavailable and launches the fault-recovery process, with corrective actions starting to be implemented. The data received from the *Material Handling Holon* corresponding to the suspended order indicates the number of remaining items to be processed by the faulty machine cell. A corresponding new job will be started by the *Order Holon*.

4.3 FMEA Holonic Module

FMEA Background Information. Regardless of the application domain, when a system, product, process or project design includes some type of a risk, the FMEA process can be used as a tool to identify and correct design deficiencies by analyzing the failure modes, their mechanisms and effects, and to propose corrective actions. Yang [16] considers that FMEA can be described as a group of activities that lead to the recognition and evaluation of potential failures pertaining to a process or a product and their effect, in a first step, and the actions that attempt to eliminate the occurrence of those failures in a second step.

Even though, several improvements of the FMEA process were made after the initial release, that led to the development of extended versions, such as: Failure, Mode, Mechanisms, and Effects Analysis (FMMEA) or Failure, Mode, Effects, and Criticality Analysis (FMECA), the underlying concepts remained the same, and are summarized below [16-17].

- *Potential failure mode* is the manner in which a system, subsystem or a component fails to meet the requirements it was designed for;
- *Potential failure effect* is the impact of the failure or the consequences if a failure happens;
- *Potential failure causes* are the circumstances, during design, manufacturing or use that lead to the failure mode; and,
- *Failure mechanism* is the combination of stresses that induce failure, where a stress can be electrical, chemical, physical or mechanical.

Wessels [18] considers that criticality analysis attempts to evaluate the consequences of failures and establish a ranking method to determine criticality level. One of the most known approaches to evaluate the criticality of a failure mode is to compute the Risk Priority Number (*RPN*), which is obtained by multiplying three factors: severity, occurrence and detection, defined below, with all these three factors being associated with the same perceived risk.

- *Severity* factor is evaluated based on the effects of the failure mode, where these effects can be related to the system (e.g., damage, repairing costs, availability, etc.), personnel (e.g., death, injury, idle time, etc.) or regulations, which are punitive actions taken as a result of certain violations. Usually, severity is measured on a scale from 1 (least severe) to 10 (most severe);
- *Occurrence* factor is evaluated based on the likelihood of a failure to happen, from unlikely to frequent. Usually, the occurrence factor is measured on a scale from 1 (least likelihood of occurrence) to 10 (certainty of occurrence);
- *Detection* factor is evaluated based on the ability to detect the failure. Usually, failure modes range on a scale from 1 (obviously detectable) to 10 (not detectable).

By analysing the components of the *RPN*, it can be stated that the risk of a failure increases when *RPN* takes higher values. As a consequence, actions like design change, material upgrade and revision of test plans can be implemented to reduce the identified risk.

Implementation of the FMEA Holonic Module. Since the *Condition Monitoring Holon* is designed for real-time detection of failures and fault-recovery, the FMEA implementation, as part of the *Condition Monitoring Holon*, emphasizes potential failure causes and associated failure mechanisms. Through real-time monitoring of the system, the *Condition Monitoring Holon* collects the data that serves to identify under which circumstances and conditions failures are likely to occur. For example, a certain failure in raw materials can be caused by temperature cycling, random vibration or shock impact. In this case, if the temperature and vibration sensors are deployed, the data collected is used by the *Condition Monitoring Holon* to establish the ranges of values for the temperature and vibration values under which the failure is likely to occur. During operations, if any of these value ranges is detected, the *Condition Monitoring Holon* takes the appropriate action to flag the unavailability of the machine or equipment for future processing until the likelihood of failure is reduced to acceptable levels.

The detection, fault-isolation, and recovery process can be enhanced by adding an *FMEA Holon* to the *Condition Monitoring Holon*. The *Condition Monitoring Holon* uses the data received from the deployed condition monitoring units and the data retrieved from the FMEA unit to assess the status of the machines and decide about their availability and the preparation for the recovery process. The *FMEA Holon* serves as a storage and processor of data and considers the following parameters, performance measures, and actions related to the potential failures of the processing machines and equipment. Using a SysML™, Internal Block Diagram, the internal architecture of the *FMEA Holon* is presented in Fig. 4.

- *Failure modes*: the *FMEA Holon* identifies and stores different failure modes exhibited by the instances of the *Machine Holon*;
- *Failure effects*: the *FMEA Holon* acknowledges and addresses the potential failure effects on the *Machine Holon*;

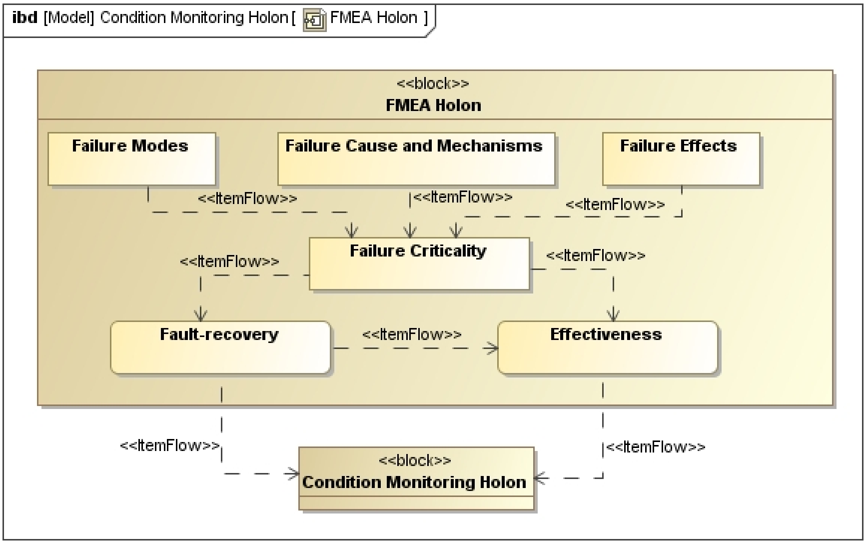

Fig. 4. The internal architecture of the FMEA Holon and data exchange

- *Failure cause and mechanism*: the *FMEA Holon* describes the potential causes or mechanisms (combination of stresses) that may induce the failure, and the different value ranges for the different mechanisms/causes that lead to the failure; as an example, if the failure cause is determined as being an elevated temperature, and the failure is likely to be induced if the temperature goes above 150ºF, then the range is defined as [150, +infinity];
- *Failure criticality*: the *FMEA Holon* calculates the *RPN* number associated with the failure which includes the measures of severity, occurrence and detection;
- *Fault-recovery*: the *FMEA Holon* provides recommended actions for fault-recovery purposes, which increase the likelihood that the occurred failure is contained, and future failures are avoided;
- *Effectiveness*: the *FMEA Holon* measures the results of implementing the recommendations by re-calculating an updated *RPN* number.

Functionality of the FMEA Holonic Module. With the addition of the *FMEA Holon*, the *Condition Monitoring Holon* is able to retrieve data related to the failure cause and mechanism, which includes the defined range, and compares it with the real-time data received from the deployed instances of the *Condition Monitoring Holon*. Out of this interaction, two failure scenarios can result, for which the data flows and the overall functional architecture of the *Condition Monitoring Holon* are presented in Fig. 5. First scenario considers that the real-time data values received from the deployed instances of the *Condition Monitoring Holon* begin to cover the predefined range. In this specific scenario, a failure is likely to occur in the system, so the *FMEA Holon* recommends the following list of actions to be considered within the system.

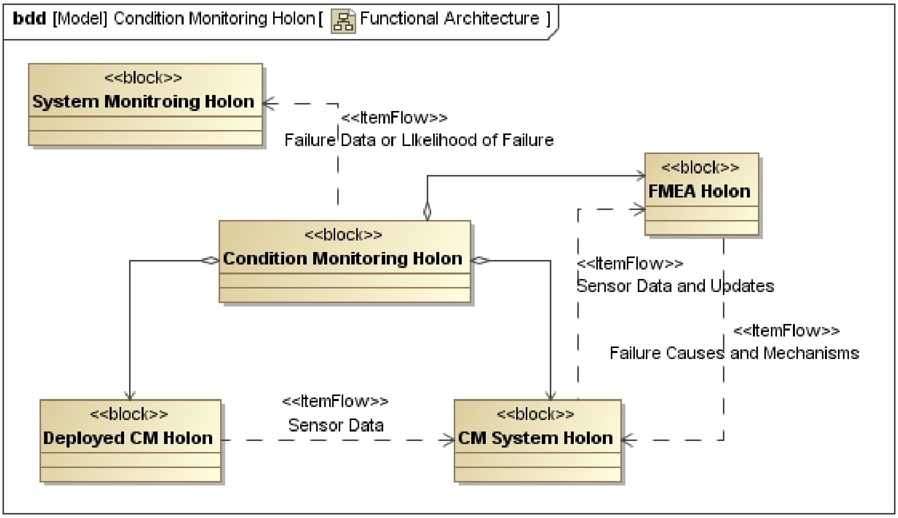

Fig. 5. Functional architecture of the Condition Monitoring Holon

- The *fault-recovery* process is to be launched with the implementation of the recommended actions.
- The *effectiveness* measure is updated; if the implemented actions were effective, then the occurrence of the corresponding failure mode should be reduced, which should result in a decrease of the *RPN* number.

The second scenario considers that a failure actually occurs in the system. This second scenario can be further organized in another two possible cases.

- If the failure mode was not found in the *FMEA Holon* database (i.e., the failure mode was not defined or occurred before), the database should be updated with the new failure mode along with its causes, mechanisms, effects, and criticality to the extent possible; also, the data collected by the deployed instances of the *Condition Monitoring Holon* is to be retrieved and will serve as an analysis basis for the failure causes and mechanism and for the definition of the pertaining value ranges;
- If the monitored condition ranges, pertaining to mechanisms, are not well defined, then an analysis of the data received from the deployed instances of the *Condition Monitoring Holon* will serve to establish new failure condition ranges, pertaining to mechanisms, and the *FMEA Holon* database will be updated.

5 Simulation Study

Two simulation models corresponding to the two holonic systems described above were implemented using the Arena® simulation environment. The *Machine Holon* included the use of 10 holon instances, each of them having associated 10 instances of *Condition Monitoring Holons*. There were four instances considered for the *Material*

Handling Holon, two for the *Equipment Holon*, another instance for the *Condition Monitoring Holon*, four different instances for the *System Monitoring Holon*, and a single instance for the *Order Holon*. The design of the simulation experiments for both models included 100 replications for two months of continuous operation simulation time. The other running parameters for the two simulation models were selected such that the systems worked at high utilization and all the potential events, such as resource failures, were sufficiently represented to obtain an accurate means of comparison between the performances of the two systems.

- Orders arrival was approximated by an exponential distribution with the mean of 30 minutes: EXPO(30);
- Number of items to be processed for each of the order was considered to be equal to 240;
- Failure rate of the physical resources was approximated by a Weibull distribution with parameters as follows, measured in hours: WEIBULL(8.5, 25.5);
- Job arrival rates for each of the machine cells was selected as coming from an exponential distribution with a mean of two minutes: EXPO(2);
- Processing time on the machine cells was approximated by a triangular distribution with the following times, expressed in minutes: TRIA(1.8, 2, 2.2);
- Time needed for performing the corrective maintenance actions, in minutes, were approximated by using exponential distributions, EXPO(40) for the first simulation model, and EXPO(20) for the second simulation model;
- Quality control sampling process used in the first simulation was able to identify the machine cells degradation process after producing 30 defective parts.

Overall, the simulation results show an improvement in the manufacturing plant metrics when real-time condition monitoring was implemented. First, the results show an increase in the utilization for the machine cells. For example, there are utilization increases of 1.52% and 1.40% for machine cell 3 and machine cell 10 respectively. Also, the overall utilization of the manufacturing plant was recorded to increase by 1.19%. The productivity of the machine cells also increased leading to an overall increase in the number of items processed by 2.09%, and the number of jobs executed by 4.23%. For example, the number of items processed increased by 2.02% and 2.38% for machine cells 6 and 10, respectively. These improvements in machine utilization and the productivity of the resources were obtained due to the fact that less time was necessary for performing fault diagnosis and identifying necessary corrective actions. In the case of the condition monitoring-enabled system, the data necessary for fault diagnosis is made available in real-time by the *Condition Monitoring Holon*, eliminating the time needed for performing the quality control sampling process. Fig. 6 presents the reported results above.

The increase in the number of jobs completed (for example, 4.23% and 4.65% more jobs completed for machine cells 3 and 7, respectively) is obtained due to the real-time job re-scheduling capabilities implemented when a certain machine cell, initially responsible for job processing, enters a degradation process (Fig. 7). Also, the results of simulating the proposed condition monitoring holonic manufacturing system showed a significant improvement of quality of the completed orders.

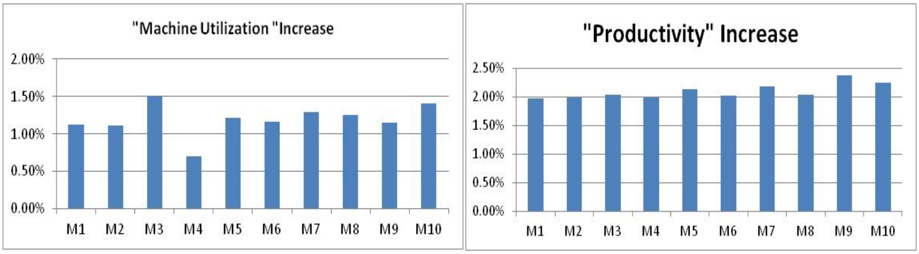

Fig. 6. Improvement in utilization and productivity when using real-time condition monitoring

The manufacturing plant defect rate, which was recorded in the first simulation model to be more than 4% (Fig. 8), decreased in the second model to a value of almost 0%. In fact, any job assigned to any machine cell will be cancelled and rescheduled immediately if the machine cell goes into a degradation process which prevents the processing of any part using a failed resource.

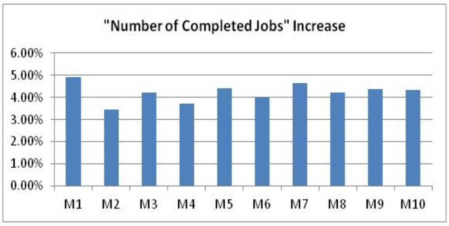

Fig. 7. Completed jobs performance

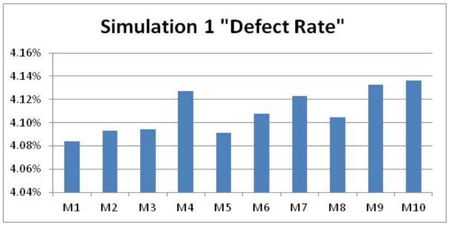

Fig. 8. The initial defect rate recorded

6 Conclusions and Future Research Directions

This work presents a holonic condition monitoring and recovery system for sustainable enterprises, which includes mechanisms for fault-detection, isolation, and recovery. The addition of an FMEA module is further enhancing the capabilities of the proposed system. The simulation results presented in the previous section show a significant improvement in terms of productivity, responsiveness, flexibility and quality when the condition monitoring and recovery system is employed. This improvement comes from the transition to a more advanced holonic manufacturing architecture that uses wireless sensor networks for real-time monitoring of resources. Sustainable enterprises need adequate models that take in consideration potential real-life scenarios and have the ability to respond with real-time solutions such that the operations of the facility are not disrupted. As future research directions, this work can be continued by investigating the impact of real-time monitoring on a more complex manufacturing environment presenting different types of resources executing jobs related to many products and facing several sources of disturbances and uncertainties such as demand, machine, equipment, and facility failures with combined FMEA scenarios associated with the processing machines, equipment, and facility.

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