Multi-agent enterprise resource planning production control methodology based on personnel health monitoring

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Abstract
This study presents a novel production control methodology using a multi-agent enterprise resource planning system that employs ERP modules as software agents for achieving enterprise-wide integration. Consequently, ERP is transformed from a decision-supporting system to a decision-making system. Based on a new data exchange framework developed in this study, five ERP modules, including health & safety and environment, human resource management, inventory control (WIP & BOM), quality control, and maintenance, are integrated as autonomous software agents. This methodology employs a wearable data monitoring device and proposes a new prototype of wireless health monitoring for production system operators and personnel; however, it can also be utilized for the entire enterprise. The proposed methodology involves monitoring, analyzing, and evaluating the performance of each work shift against real-time personnel health status data and their location on the production system's shop floor. This paper describes how the presented Multi-Agent Enterprise Resource Planning Production Control (MAERPPC) methodology integrates commercially available enterprise resource planning systems using multi-agent production control systems and existing information technology. In addition to the benefits mentioned above, the proposed methodology considers the health status of personnel in different work shifts and its impact on the productivity and performance of the production system.

Keywords
ERP, multi-agent, production control, personnel health, bioactive sensor.

1. Introduction

In the industry of the modern, technologically advanced world, where competition plays a significant role, one of the most important goals of managers is to maximize the efficiency of resource use. In this regard, the optimal health status and maximum performance of personnel and employees, one of the organization's most valuable resources, have taken on added significance. Therefore, monitoring and surveillance of the parameters that determine the health of personnel, which can significantly impact their productivity and organizational performance, has received considerable attention.

For a few years, many authors have been interested in the integration of the human factor in production activities with approaches based on mathematical models (Bayesian networks, fuzzy logic, mathematical programming...) because the decisions taken without integrating the human factor do not allow us to reach the obtained results Moreover, the development of digital twins and cyber-physical systems requires the development of such studies. Some of the prominent fields and studies in this context are as the following: mathematical modeling of human factors' impact on production and/or maintenance activities [1–4], integration of human factors in the manufacturing design process and Industry 4.0 tools [5,6] and multi-agent based systems for ERP [7,8] However, current monitoring methods are insufficient for assessing or enhancing the health status of personnel and play no major influence in an interconnected model with organizational information systems like ERP. In recent years, numerous studies have been conducted to explain the health status of shift-work employees [9–11]. To the best of the authors' knowledge, no research on the relationship between work status and health conditions in different work shifts and the performance of a production system has been conducted.

Numerous decades of research on efficient production control strategies have led to the development of the methodologies currently employed in state-of-the-art production systems. Particularly significant is the evolution of computer hardware technology that has resulted in the consideration of IT-based programming [12].

The term ERP was first used in the 1990s by the Gartner Group [13], but enterprise resource planning systems actually have their roots deep in the manufacturing industry and can trace their history back to the 1960s. ERP systems are packaged software applications that support most of a company's information needs within and across functional areas in an organization [14]. Modern ERP systems serve as the foundation for a wide range of e-business models within one company as well as throughout the value chain [15]. In ERP systems based on modular software structure and a centralized database, information flows in manufacturing, finance, sales, distribution as well as human resources processes that can be integrated in real-time [16]. The ERP modules are considered to function as agents in the current work. The agent is an autonomous entity capable of acting on itself and its environment. Such an agent can communicate in a multi-agent environment and observe, interact, and share data with other agents. Similarly, a multi-agent system (MAS) is a group of autonomous agents collaborating to achieve a shared goal of solving an assigned problem [17,18].

In other words, a software agent is an autonomous, self-contained software module that performs tasks assigned by a human user. To ensure the completion of assigned tasks, the agent can interact or communicate with other applications and software agents within the same environment [8], [19].

Obviously, the agent-based system is the software of the next generation, capable of dynamically adapting to changing business environments. This system claims to be capable of resolving various business issues and can be used in various applications, including supply chain management (SCM), health care and patient monitoring, and process control [20]. Due to their capacity for adaptation, ERP systems can be considered more intelligent than previous models. They enable autonomous interaction with the surrounding environment and autonomous action while collaborating with other systems. By employing agents, ERP systems can become more intelligent. By taking cloud computing into account, this issue is almost clear [21–23].

Taking into consideration the advantages of agent-based systems, in this study, agent-based systems cooperating with ERP modules are used to investigate the working conditions of employees. Previous methodologies used more straightforward techniques based on worker health or workplace conditions [24]. Other existing methods for identifying, eliminating, substituting, and controlling occupational hazards employ smart hardware and software. Like wearable devices, connected worker solutions provide workers with contextual information and decision support [25].

Leading companies have employed prior health monitoring devices for developing sophisticated devices and technology for enhancing workplace health status and preventing occupational hazards. For instance, wearable sensors from the Honeywell BioHarness physiological monitoring system have been used to track workers' physical location and the temperature, respiration rate, heart rate, activity, and user posture [26]. Other examples include Guardhat's smart hardhat, which can measure multiple parameters, including pressure, temperature, proximity, altitude, and noise [27]. At the same time, Reactec's HAVWEAR wearable watches are developed to assess and manage hand-arm vibrations (HAV) and contain sensors for occupational hazards such as noise, vibration, dust, and gas. Utilized by workers while operating machinery [28], The Spot-r Clip, presented by the Triax Technologies Spot-r platform, is a clip-on device worn by staff, laborers, and workers to report injuries, safety incidents, and hazards [29].

To the author's knowledge, however, not even cutting-edge technology has incorporated the concepts of multi-agent systems integrated with ERP modules for real-time monitoring of personnel health conditions on the shop floor of a production system or measured its effect on the efficiency and performance of the production system and work shifts. Resolving this issue would significantly improve current capabilities and merit a thorough investigation.

In this study, developing a multi-agent production control framework integrated with ERP that employs a physical cyber-based personnel health monitoring system that employs efficient, accessible, readily available, and relatively inexpensive technology from Samsung bioactive sensors is proposed as a solution to this problem. Presenting the model (Data-exchange framework), tools, and control method is the main subject of this research. This methodology summarizes the health status of personnel using Samsung bioactive technology, which can be easily installed on personnel and workers of a production system by using available wearable data observing devices such as a smartwatch with an Android-compatible smartphone. Consequently, this method eliminates the limitations imposed by hard-wired links and significantly reduces the power consumption of the long-term monitoring system. As an agent, this system can acquire, transmit, record, and display real-time healthcare conditions of personnel, such as blood pressure, blood oxygen, heart rate, beats per minute, ECG signal, stress, and alertness, among others, for the ERP's HSE module [30].

Wireless technology significantly enhances the mobility, adaptability, and usability of the staff's health care monitoring system. Alternatively, the related shop-floor monitoring modules, which are introduced as another agent for ERP in the context of production control developed in this paper, can continuously generate production data such as scrap rate, rework rate, machine breakdown, production rate, semi-product quality, and finished product quality for each work center and work shift in real-time.

The proposed production control framework can integrate and transfer real-time data between cyber-physical objects on the shop floor and various ERP modules, such as HSE and others.

Moreover, the agents above can independently communicate and transfer data in real-time. The previously stated characteristics allow the proposed framework to evaluate the connection between staff health conditions and the productivity of each work shift in various work centers on the shop floor. Therefore, the decision-maker agent in ERP optimizes the allocation of personnel in the appropriate work shift based on their history of best health condition as well as work performed regarding minimum waste (scrap, rework, and others) and output rate, which depends on the health condition of the personnel. This article's main novel contribution, which, to the best of the author's knowledge, is noticeably lacking in previous works.

The procedure efficiency increases when the proposed method is implemented in production systems. In addition, the proposed method reduces work-related accidents caused by workers' lack of environmental awareness during inappropriate shift schedules, resulting in lower insurance and healthcare costs for production systems and the whole enterprise.

2. Methodology

The components of the proposed MAERPPC methodology are described in the following three sections:

(i) **Data-exchange framework:** The developed framework for data exchange between the various components of the manufacturing system, such as Machine Data Acquisition (MDA), Production Data Acquisition (PDA), Manufacturing Execution System (MES), and real-time data exchange between related modules of ERP, such as Health, Safety, and Environmental (HSE) module, Human Resource Management (HRM) module, inventory (WIP & BOM) control (IC) module, quality control (QC) module, and Maintenance (M) module based on personnel health monitoring is presented.

(ii) **Tools:** The appropriate tool and its data acquisition components are detailed for the framework's efficient operation.

(iii) **Method:** The relationship between the framework's components and its data exchange model, appropriate health platform, and architecture of personnel health data gathering model in MAERPPC methodology, which leads to integration with ERP modules, is presented. This section utilizes the data exchange framework developed in the previous section.

2.1. Data-exchange framework

Figure 1 depicts an example data-exchange framework for production control that will be used to develop the proposed data-exchange framework [31]. This framework is designed for the composition of a MDA system, a PDA system, a MES, and an ERP system. The MES is used as the central data hub in this framework for data exchange to connect the physical manufacturing and production system with a multi-agent system. The MES receives continuous updates from the ERP system on planning data such as route sheets, shift plans, and production orders for various products, as well as the current state of planned operations, job processing data, machine status data, and personal information from the PDA system [31].

To integrate the relevant and required ERP modules into the IT architecture of a manufacturing company and to enable the data exchange between the real system and the simulation model based on the health monitoring of workers and personnel, the Multi-Agent Enterprise Resource

Planning Production Control (MAERPPC) framework based on personnel health monitoring was developed (Figure 2). To develop this data-exchange framework and all the components and parts used in the exemplar data-exchange framework (Figure 1), the required ERP modules and relevant cyber-physical systems components for providing the intended sensorial data have been introduced and utilized.

2.1.1. Integration with ERP

Considering the agent as a computational system located in an environment that can act independently to achieve its design goals in that environment, the interoperability of multi-agent systems implies that each agent can be influenced by other agents or humans to carry out tasks in accordance with their goals [32–34]. To this end, it can be concluded that the current framework's role for ERP modules and their performance, including autonomous data exchange between them, has been upgraded to agents and multi-agent systems.

Notably, the cost of implementing Multi-Agent Enterprise Resource Planning (MAERP) is significantly less than that of implementing commercial ERP software. The MAERP will simultaneously take advantage of the current information systems that are mature from a functional standpoint and error-free from maintenance, modification, and best practice perspective. In addition, adding smaller program modules as software agents to existing information systems will not necessitate a substantial financial investment. The MAERP implementation will incorporate each department's current technology utilization expertise and culture [8].

In this framework, the communication method between ERP modules as management and decision-making agents and data generated by sensorial data acquisition tools are categorized as follows:

- **HSE:** The ERP's health, safety, and environmental module receive continuous updates on personnel health conditions from shop-floor employees and personal information data from ERP's HRM module.
- **HRM:** In ERP, the human resource management module receives the following data: Personal information data sent from worker(s) to PDA, from PDA to the MES, and from MES to the HRM.
- **IC:** The ERP's inventory (WIP & BOM) control module receives the online status of the entrance and exit gate of the warehouse holding raw material stock, online status of the entrance and exit gate of the warehouse holding finished material stock, planned operations (WIP) and job processing data (finished jobs) from the MES while MDA acquires machine status data from the machine(s) and job processing data from the exit gate from the shop floor and sends these data to PDA and from there, these data are sent to the MES and from the MES to the IC in the ERP.
- **QC:** The quality control module of ERP receives three groups of data, including raw material quality before the manufacturing process, semi-finished product quality during the manufacturing process, and final product quality before shipment to customers, as follows:

- Status of raw material quality and quality condition(s) of inventory during storage received from raw material stock;
- Condition of semi-product(s) from material buffers on the shop floor;
- Status of finished jobs, goods, and product quality from finished material stock;

The MES continuously collects this data for each shift of personnel and workers and sends it to the QC in the ERP.

- **M:** The maintenance module of ERP continuously receives machine status data updates from the MES. The collection and transfer of this shop-floor data to the MES have already been described above.

2.2. Tools

Samsung bioactive technology is utilized to collect personnel health conditions. To this end, the authors of this paper recommend using the Samsung Galaxy Watch4 smartwatch, which offers a wide array of sensors that collect the desired data within a data-exchange framework, as well as extensive platform compatibility and a data transfer environment.

2.2.1. Health data acquisition and sensors

Smartwatches that collect, display, and transmit information, such as the user's location and health status data, were deemed suitable for this study. In addition, further benefits of these devices, such as their ease of use, low energy consumption, ready availability, simplicity of use for personnel, the concentration of a significant number of required sensors, the availability of a wireless data sharing infrastructure, and their capacity to collect a portion of the information required by the current methodology, made their application suitable for the present work.

Samsung Galaxy Watch4 classic smartwatch with Wear OS Powered by Samsung, 1.18GHz dual-core Exynos W920 5nm processor, and WLAN connectivity including Wi-Fi 802.11 a/b/g/n, dual-band, was used in the developed methodology. Bluetooth consisted of Bluetooth® 5.0, A2DP, LE, and GPS with A-GPS, GLONASS, GALILEO, and BDS. The device was compatible with Android 6.0 or later, with a RAM of above 1.5GB.

The device also comprised an accelerometer sensor, barometer sensor, gyro sensor, geomagnetic sensor, light sensor, optical heart rate sensor, and electrical heart sensor, including a bioelectrical impedance analysis sensor [30].

Figures 3 and 4 depict a few of the aforementioned Samsung bioactive sensors.

Some of the data collected by this tool, the sensors employed, and their significance to the health status of the user are described below [30]:

- Blood pressure sensor: utilizes an optical heart rate sensor known as the photoplethysmography (PPG) sensor to measure blood pressure.
- Electrocardiogram (ECG) sensor: uses an electrical heart sensor that measures electrocardiography signals.

The Samsung bioactive sensor measures real-time ECG and blood pressure. After initial calibration, the sensors assess blood pressure quickly. This sensor can also examine abnormal heart rate and rhythm via ECG and transmit data directly to a smartphone for easy sharing.

- Blood oxygen acquisition module: measures blood oxygen levels from the wrist; the Galaxy Watch4's built-in blood oxygen measurement allows for continuous monitoring of oxygen levels in the bloodstream. The relationship between oxygen saturation and physical performance is direct, so monitoring blood oxygen can help workers and personnel maintain health.
- Assesses how the body performs during a workout (in this case, intense physical activity) and measures the heart rate as the individual recovers.
- Watch-mobile interworking measures heart rate and calories, display the data on the larger screen of the user's phone in real-time, and transmits the data directly to a compatible smartphone for easy sharing.

Consequently, this tool can be used to collect the individual and collective health status of an organization's personnel and workers. Thus, the effects of this situation on the conditions and performance of the production system can be analyzed. This tool has considered the role of a health data acquisition device within the production control framework.

Other cyber-physical systems can provide additional information regarding the performance of the production system, including scrap rate, rework rate, machine breakdown, production rate, semi-product quality, and finished product quality [35–38].

2.3. Method

The method is integration enhancement based on personnel health parameters affecting on production flow of materials and quality of semi-products in the production line. This methodology component is centered around developing an efficient, simple, cost-effective, and sustainable mobile health status technique based on observing infrastructure and devices. The method proposes a wireless health observation and monitoring prototype system that includes the personnel's real-time location, blood oxygen, blood pressure, stress, heart rate (BPM), and ECG signals. This system combines an ERP module with Samsung bioactive technology, Wi-Fi, GPRS, and GPS wireless technology.

The wireless mobile healthcare system is a flexible system that allows users to monitor the necessary biological signals (blood oxygen, blood pressure, stress, heart rate (BPM), and ECG signals) in real-time. It transmits the analysis results directly to the remote ERP module (in this case, the HSE) via the mobile wireless communication device. With the aid of the health platform (official software for receiving, process, and sharing health data and information installed on compatible smartphones of users and personnel) [39] (Figure 5) and based on the Personnel Health Status Data Transfer (PHSDT) model utilizing in the MAERPPC methodology, personnel health data is transferred (Figure 6).

Through the wireless physiological signal acquisition, personnel and workers can determine their health status using a smartphone and an authorized health platform, as well as transmit preliminary analysis results and other acquisition data to an authorized remote HSE server in the ERP via the Wi-Fi and GPRS link.

This system can acquire, transmit, record, and display personnel's precise location and health parameters. The wireless technology significantly improves the mobility, adaptability, and usability of the health monitoring system for healthcare personnel, while the Samsung bioactive sensor technology reduces power consumption.

Consequently, this infrastructure can be utilized for numerous applications, including:

- Continual personnel and worker monitoring on the shop floor and throughout the production system or enterprise;
- Computer-assisted decision-making system utilizing other simultaneous shop-floor and production system data acquisition;
- Prolonged environmental monitoring;
- Emergency medical care, depending on the situation

3. PHSDT model in MAERPPC methodology

This section mentions the structure of the wearable data-observing device, the data-transmitting medium, the data-processing machine, and the remote monitoring and control module.
This model consists of the components listed below:

- The smartwatch-mounted Samsung bioactive signal acquisition device;
- A Bluetooth module;
- A smartphone;
- A health platform;
- An ERP module (HSE).

The model depicted in Figure 6 could be used to log data and establish trends for an employee utilizing multiple types of sensors based on Samsung's bioactive technology - which has already been introduced and evaluated - and the worker's smartphone.

4. Discussion

Here, a simple illustration of how easily the proposed methodology can be implemented is provided. This illustration consists of three fundamental elements: (i) data exchange framework, (ii) tools, and (iii) method.

In the data exchange framework, the MES is considered the central data hub for data transfer between the physical production elements in the production system and the multi-agent system. These data consist of shop-floor and production-wide information. At the same time, the data transfer regarding the health status of personnel was designed to occur directly through the web and IT data-transfer infrastructure (based on the introduced PHSDT model) to the information system of the HSE module in ERP. Integration and data transfer between some ERP modules and/or hyperphysical components in shopfloor have been clearly described in integration with ERP components.

In the tools section, a suitable tool for collecting personnel health status data for methodological purposes was introduced by considering a proper set of characteristics, such as the ease of mounting on personnel, the variety of health status data that can be collected by the sensors used, and the availability and reliability of the data transfer infrastructure.

In the method section, a new data flow integrated with some ERP modules as software agents has been developed to form the execution of multiple actions (or commands) via agents, resulting in a multi-stage, structured conversation between agents.

Using the methodology developed in this paper, the ERP will be able to utilize data exchange between the modules mentioned as decision-making agents. Each related module as a software agent is used to evaluate the activity and performance of the production system, including scrap rate, rework rate, machine breakdown, production rate, semi-product quality, and finished product quality concerning each work shift, taking into consideration the health status of personnel and workers who have worked each shift. This method facilitates the extraction of this information. In addition to the impact of personnel health status on the performance of the production system, it is possible to monitor the data above using predefined rules, based on the best practices in ERP modules, appropriate decisions, and commands. This data also includes an examination of changing shifts or working hours based on the status of each employee to increase system efficiency and staff productivity. Additionally, this information can be reported to system administrators.

The ability to compile health records for all workers and personnel, as well as the ability to develop different programs to measure parameters based on age and gender in predetermined intervals, can result in an improvement in the health status of production staff and company personnel, as well as a reduction in insurance costs for staff and the organization. This methodology can be executed by HSE in its capacity as an executive agent and it should be noted that it comprises the following capabilities, which can be used to assess its performance:

- Obtain health status signals via Samsung Bioactive sensors;
- Initial processing and display of collected health data regarding an employee's health condition on a smartwatch;
- Transmit the collected data via a smartphone's Bluetooth wireless link;
- Export data from a smartphone via GPRS or Wi-Fi to the HSE module of ERP through the health platform;
- Final processing with a holistic view as a result of integrating all the data collected by the data-exchange framework from the current state of the production system and the health condition of the personnel into the ERP;
- Decision-making is based on best practices and predefined rules in the relevant ERP modules as decision-maker agents -or enterprise managers- and applies these decisions to the production system.

4.1. Effectiveness and Benefits

The defining characteristics and significant Effectiveness and benefits of the proposed methodology can be described as follows:

- High rate of data and information transfer;
- Concurrent information reading and transfer ability;
- Eliminates the physical constraints imposed by a wired connection;

- Drastically reduces the power consumption of the system for long-term monitoring;
- Ability to monitor the health status of personnel during work shifts based on the schedule;
- Matching and evaluating the efficiency of each shift (based on criteria such as scraping and reworking) and production rate;
- Possibility of optimally adapting personnel health conditions for managerial or system decision-making based on predefined scenarios;
- Based on the management plan, it is possible to provide limited production system performance and shop-floor data information to the relevant departments (the information is provided to the specific user, and, if necessary, information is provided in a read-only format).
- Due to the internet-based data transfer platform, based PHSDT model, all the benefits of cloud computing systems, such as cost reduction, increased speed, high scalability, high security, reliability, and high performance, are conceivable for this system's application to the employees' health status.

4.2. Challenges of implementing

The fundamental challenges of implementing the MAERPPC methodology can be categorized in the following main areas:

- Network and communication infrastructure - data exchange media
- Correct functioning of the hardware and equipment used
- Upgrade and development of ERP modules to software agents
- Application of collected data and information in ERP modules as software agents

4.3. Application

The methodology presented in this research is highly applicable for those industries where the accuracy and speed of manpower operations in production lines or work centers have a high impact on the quality and cost of produced products.

5. Conclusions

This paper proposes a multi-agent production control methodology based on the health status of workers and personnel for each work shift on the shop floor, which enables the integration of an ERP system.

This methodology utilizes five ERP modules with specialized knowledge to collect pertinent data and information based on their best practices as a set of software agents. It also uses wearable data monitoring devices developed by Samsung bioactive technology and the PHSDT model to enhance the integration between the worker(s) on the shop floor and the HSE module in ERP for real-time personnel health status data share. Consequently - based on the cooperation of agents, information systems, and managers - implementing the proposed MAERPPC methodology will result in the capacity to make timely decisions in various organizational situations and scenarios.

The first novelty is the use of Samsung bioactive technology as an effective tool for real-time personnel health data collection and monitoring in conjunction with worker and personnel locations. The second is real-time data exchange between different components of the framework and related ERP modules, to use them as decision-making agents by receiving data, evaluating it, and making decisions based on the dynamic and changing conditions of the production system.

Consequently, it can determine how the health status of personnel affects production system conditions. The mentioned methodology and its data exchange framework are the initial steps toward real-time monitoring of personnel health status on the production system's shop floor and its impact on the production system's efficiency and performance and its work shifts in multi-agent ERP systems.

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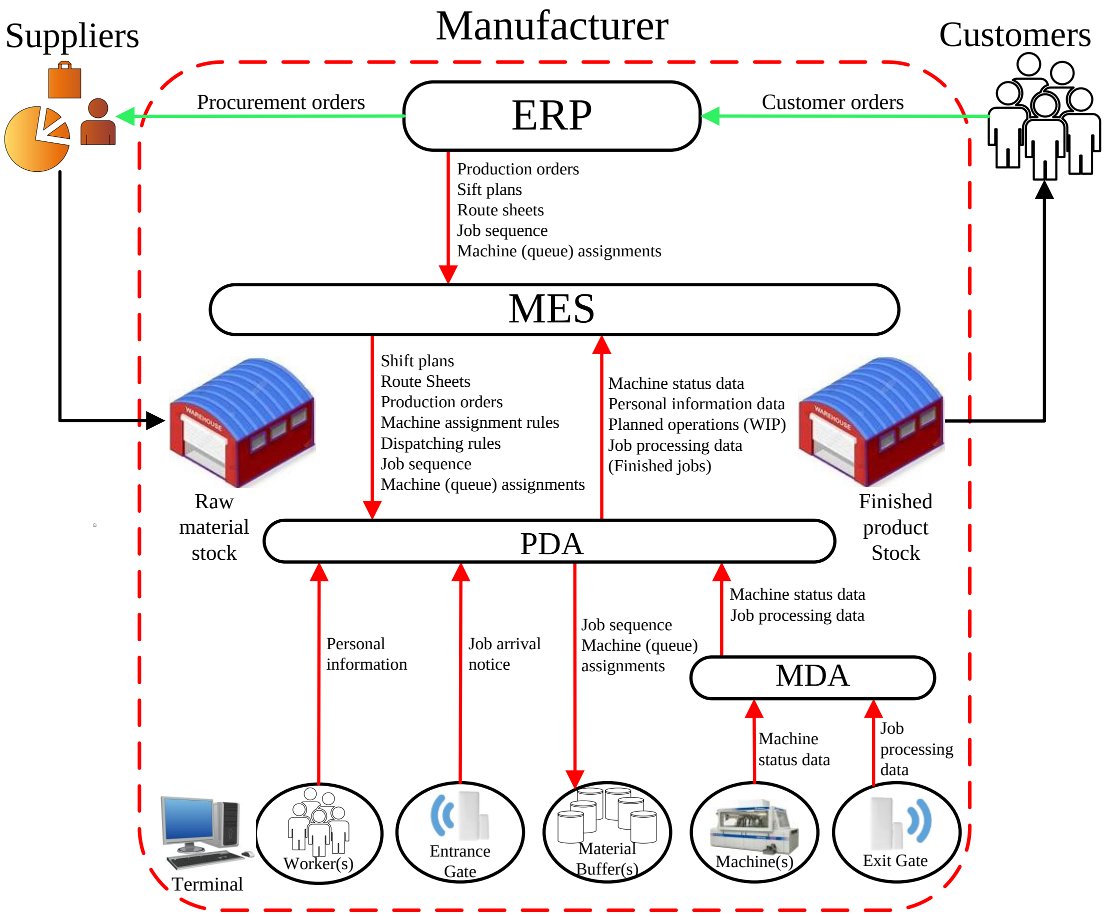
Figure 6. PHSDT model in MAERPPC methodology



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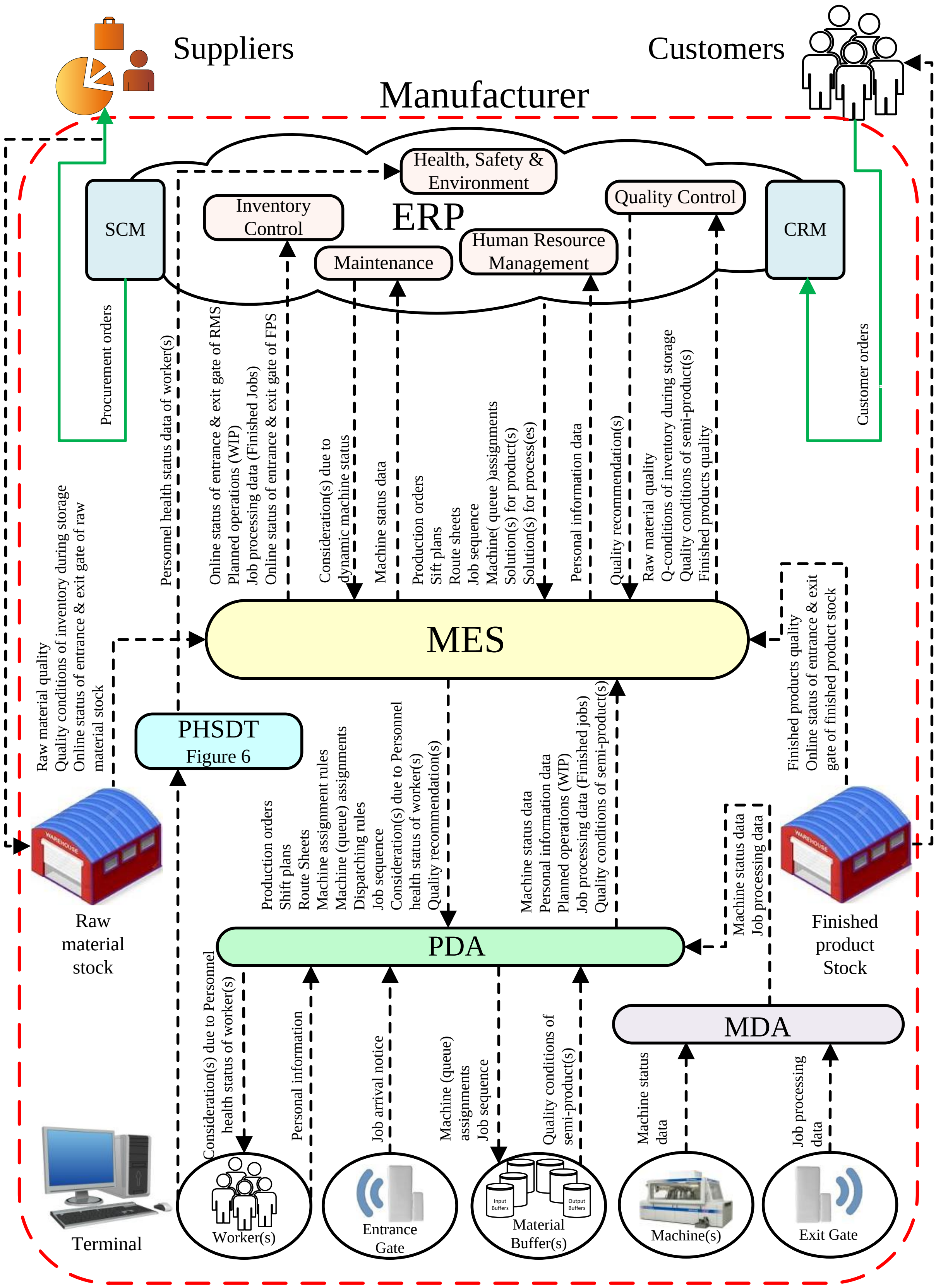
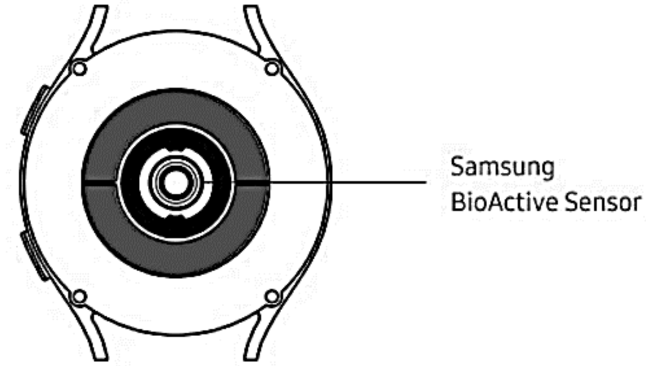


Figure 2. MAERPPC-based personnel health monitoring framework

(PHSDT: Personnel Health Status Data Transfer)



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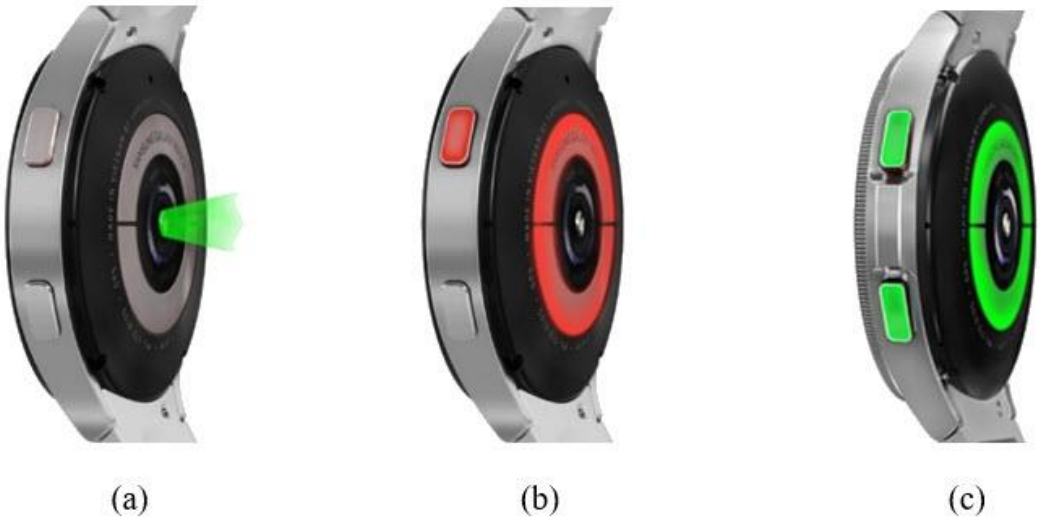

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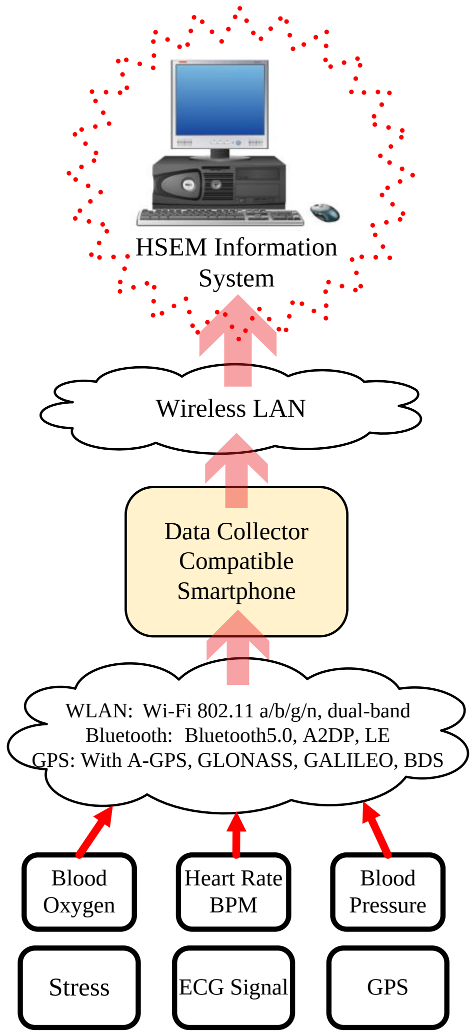

Figure 6. PHSDT model in MAERPPC methodology

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