EAI Endorsed Transactions
on Digital Transformation of Industrial Processes Research Article EAI.EU

Integrated Manufacturing Management Platform

Gaspar Vieira[1], Miguel Ângelo Pereira[1,2], Leonilde Varela[1,*], Goran Putnik[1], Manuela Cruz-Cunha[2]

[1] Algoritmi Research Center/ LASI, University of Minho, Guimarães, Portugal
[2] Polytechnic Institute of Cavado and Ave, Barcelos, Portugal

Abstract

INTRODUCTION: This paper presents a brief overview of the Integrated Manufacturing Management Platform (IMMP), designed to enable dynamic, real-time integration of supply chain and manufacturing management across multiple factories, workstations, and external business partners. The platform fosters interoperability and shared decision-making across strategic, tactical, and operational levels, leveraging integrated middleware comprising both hardware and software components, as well as associated technologies and tools.
OBJECTIVES: The primary objective of this work is to describe the development and capabilities of the IMMP, highlighting how it supports collaborative and integrated manufacturing planning, scheduling, monitoring, and control. The platform aims to enhance joint manufacturing management by enabling information sharing and process coordination among a distributed set of stakeholders.
METHODS: The IMMP was developed using Microsoft Visual Studio to facilitate dynamic updates to its information, tools, and functionalities. The underlying databases were implemented in SQL Server Management Studio and iteratively refined to accommodate evolving platform requirements. The system architecture is based on modular components deployed across participating factories and work centers, supported by smart objects and appropriate interfaces for seamless integration and communication.
RESULTS: The resulting platform offers a fully integrated environment comprising multiple modules and functions provided by each collaborating entity. These modules support various tasks such as integrated manufacturing planning and scheduling, leveraging smart technologies and networked organizational structures. Data collected from the participating network of factories and facilities enabled the validation of the platform's core functionalities and guided successive improvements.
CONCLUSION: The IMMP demonstrates strong potential to support real-time, collaborative manufacturing management across diverse stakeholders. Through its modular, scalable, and dynamic architecture, the platform enhances interoperability and decision-making across all management levels, laying the foundation for more responsive and integrated industrial operations.

Keywords: integrated management, monitoring, control, dynamic and real time based platform

Received on 12 March 2025, accepted on 07 May 2025, published on 12 May 2025

doi: 10.4108/

*Corresponding author. Email: leonilde@dps.uminho.pt

1. Introduction

In this paper, the developed Integrated Manufacturing Management Platform (IMMP) is briefly described and illustrated, based on the results obtained from an industrial application. The IMMP is based on a dynamic and fully integrated architecture for enabling real-time based dada acquisition, processing and analysis by a set of entities interacting through a networked environment, permitting interconnection and interoperability among a more or less widened set of collaborating stakeholders, and underlying knowledge and databases and associated local management systems.

The IMMP allows, among other management functions, the exploration, processing and joint analysis of data, for instance related to equipment use and breakdowns, acquired in real time from the shop floors, along with other data related to production work orders, which is fundamental to support production planning and scheduling, along with maintenance actions planning and programming, integrated with production plans, among other collaborative management functions among a set of stakeholders.

The IMMP architecture is based on a decision-making methodology that enables to further jointly identify the critical equipment and support the definition of the maintenance strategy that should be used on each work centre and underlying machines accordingly, and a system, which facilitates the transfer of information and specialized knowledge between maintenance technicians and other Company's business partners across different manufacturing plants.

The joint decision mechanisms to support overall management and production planning through the developed IMMP is based on a set of economic, social and environmental KPIs for enabling a proper decision-making process, at different management levels, from the strategic to the operational level, namely based on energy consumption, and CO2 measuring, among several other measures at the local factories and underlying equipment.

The IMMP's information architecture allows the sharing of past learning experience, for instance, based on a repository of historical data, to support the joint production and maintenance management activities, taking into account different kind of performance indicators, and the identification of problems and solutions for performance improvement and joint manufacturing and management tasks planning. The equipment criticality analysis does also enable the adoption of preventive actions, namely preventive and further predictive maintenance (PrevM, and PredM) strategies, when financially and strategically advantageous, for instance to prevent the occurrence of accidents, such as injuries, among other negative environmental impacts.

The developed IMMP aim at contributing to increase the overall industrial management and equipment useful life planning regarding reaching sustainable global Company's goals, along with local factories ones, enabling to contribute to the reduction of the number of breakdowns and the associated downtime of equipment, leading to a lower consumption of energy and to an increase of products' quality, besides other advantages, namely related to the general satisfaction of workers, and the increased performance of decision-making tasks. All these gains are reached by applying collaborative principles and practices to reach improved solutions together. These solutions will have a direct impact on the productive availability and performance of a Company, enabling to manufacture products with higher quality and to meet the needs and requirements imposed by internal and external Company's stakeholders. This is considered to be of upmost importance currently, in the digital age, while companies are increasingly facing national and international pressure of demanding markets, intending to enable and promote a sustainable development of each other worldwide.

In this paper, the implemented IMMP prototype is illustrated through an application example, to show its usability and advantages when used in a Company intending to integrate several management functions, supported by appropriate and innovative technology, envisioning its transition to the digital era, while promoting and contributing to sustainability goals.
To this end, the developed IMMP includes a set of modules, for instance, to support integrated production and maintenance orders processing, through the use of appropriate decision support methodologies and tools, along with varying kind of planning and scheduling methods, which are supported and enriched by the use of intelligent techniques, for properly carrying out production activity control (PAC) functions.

In order to properly expose the contents underlying this paper, the remaining of this paper is organized as follows:
Section 2 briefly refers to integrated manufacturing management fundamentals, by starting with its contextualization in the scope of engineering – manufacturing and management, namely, to permit integrated manufacturing and maintenance orders planning and scheduling.
Section 3 briefly describes the developed platform (IMMP), by presenting the general platform's architecture, along with main underlying hardware and software, and by further illustrating some main platform's interfaces. Section 4 presents a general discussion about the IMMP purpose, and the main conclusions concerning the IMMP prototype developed are further summarized, along with some planned future work.

2. Integrated manufacturing management

Integrated Manufacturing Management (IMM) consists on a more or less complex manufacturing management process that integrates two or more manufacturing management functions. Manufacturing Scheduling (MS) is one of such main manufacturing management functions that refers to the planning of the execution of a set of jobs and the underlying operations, usually also referred as tasks, during a considered time horizon, on specific manufacturing resources, usually defined as machines or processors, and which can be locally available at a given shop floor or geographically distributed among factories or companies, in order to reach a simple or compound performance measure. The tasks can be sequential and/or occur in parallel, among the production resources [1].

Other definitions of Manufacturing Scheduling are presented in [2], where Manufacturing Scheduling is described as the part of the MPC (Manufacturing Planning and Control) that is responsible for the distribution of the operations by available resources, in order to maximize one or more performance measures. Pinedo & Chao (1999) [3] define Manufacturing Scheduling as the process that distributes limited resources across activities, in order to optimize the company's productive capacity, or any other performance measure. Meanwhile, Baker & Trietsche (2009) [4], describe Manufacturing Scheduling as the decision process that seeks to answer the questions: "What is the best way to distribute resources across operations, to optimize a given performance measure? What is the manufacturing sequence and/or production schedule that optimizes a given performance measure?".

Scheduling problems belong to a much broader class of combinatorial optimization ones that are difficult to solve, being called as NP-hard problems [2]. These problems are characterised by having a vast set of possible solutions, which have to be explored in the space of possible solutions for the problems.

Besides being combinatorial optimization problems, MS problems are also dynamic, due to the dynamisms that arises from the real time arrival of new tasks to be scheduled and further to the availability of the production resources, which does also dynamically change over time. These two aspects combined turn industrial scheduling problems quite difficult to solve, which are thus usually solved by using different kind of heuristic methods, for instance based on constraint programming or widened set of diverse types of other heuristics or meta-heuristics, such as, Genetic Algorithms, Simulated Annealing or Tabu Search, among other approaches, for instance based on Neural Networks, or Fuzzy Logic, among others [5,6].

Job shops are production systems' configurations, which are arranged in such a way that permits them to take a superior advantage of more or less diversified production and in varied quantities, generally in relatively small quantities. These manufacturing systems are usually arranged according to a functional logic, e.g., grouped according to the functions or processes they perform, enabling different workflows, which provides this kind of production system a popularity or relative advantage when compared to other types of configurations or production systems, more limited or oriented to some kind of products of product families, such as the flow shops.

Although, similarly to what happens in other kind of manufacturing systems, in these kind of job shop manufacturing environments, things do also rarely go as expected. This can occur due to several different reasons, for instance due to cancelled scheduled jobs and/or to the arrival of new jobs. Moreover, usually does also happen that given resources become unavailable and/or that new resources are considered. Besides, some other disturbances may occur in the shop floor, namely some scheduled task that takes more or less time than planned, or tasks that do arrive earlier or late. Further, other turbulences that may happen can be related, for instance, to machine failures, to operators' absence or to the unavailability of tools and/or materials.

Besides, also some given production schedule might become unfeasible because of some other unforeseen real time situation occurring in the shop floor. When this happens, a new schedule has to be generated to restore the manufacturing system performance, by executing rescheduling, dynamic scheduling or also so-called a real-time scheduling (Madureira, Ramos & Carmo-Silva, 2003) [7].

In manufacturing, scheduling problems are continuous by nature and a solution will quickly become obsolete. For example, a number of jobs are scheduled, and before all the jobs are processed, new jobs are released on the shop floor, making the solution obsolete before even being executed. Considering that classical, static, scheduling becomes non-optimal as soon as new manufacturing orders are launched into the shop floor (Goren & Sabuncuoglu, 2008; Ouelhadj & Petrovic, 2009) [8,9], it is necessary to find ways to adapt scheduling solutions to the dynamic nature of the problem. Dynamic scheduling can be classified as Reactive, Predictive-Reactive and Proactive Scheduling, depending on how the initial solution is conceived and how it is adapted to changes in the characteristics of the problem (Aytug et al. 2005) [10]. Whenever it is necessary to adapt the solution to the changes in the problem, it is important to determine if an obsolete solution can be adapted to accommodate the changes in the problem, or, if it is necessary to devise a completely new solution. Finally, it is necessary to determine when a solution is considered obsolete, that is, if the rescheduling is event-oriented, for example, whenever there is a change in the characteristics of the problem, or, if the rescheduling happens periodically.

There are different kind of approaches that can be used for establishing production schedules, varying from enumerative algorithms to the application of simple priority rules. Moreover, these approaches can be based on pure mathematical programming models or use simulation technique among other kind of approaches (Vieira, Varela, & Putnik, 2012) [11], for instance based on multi-agents and collaborative learning [12, 13].

Integrated Production and Maintenance Scheduling (IPMS) is considered crucial nowadays, in the context of the Industry 4.0 [14]. The IPMS is, in fact, a fundamental subset of a general broader collaborative scheduling concept, proposed, which besides including the necessity of integrating the production orders and maintenance tasks, among others, does further usually require or imply: dynamic/ agile, decentralized, distributed, intelligent/ predictive, and real-time based scheduling, along with parallel programming approaches and technology [1, 15-17] namely supported by High Performance Computing (HPC) [1, 18].

In the literature, some contributions exist about integrated production and maintenance [19-23]. Also dynamic and/ or real-time based, separated or combined, approaches for supporting manufacturing scheduling (MS) have been increasingly put forward, during the last decade [16, 23-29], as well as distributed and/ or decentralized scheduling methods and systems [26, 30, 31].

The parallel and the intelligent or predictive approaches, mainly through AI-based approaches and tools, are also getting a higher attention currently in the Industry 4.0 [32-40], along with a varying kind of other approaches, namely based on different types of heuristics and meta-heuristics [40-47].

Some main contributions from the literature about integrated manufacturing management, with a special focus on the integration of manufacturing scheduling with other management functions are summarized in the Table 1.

Table 1. Resume of main contributions from the literature about integrated manufacturing management

Authors/ sources	Main Contributions
Lopes et al. (2022) [1]	Defined Integrated Manufacturing Management (IMM); explained the complexity of Manufacturing Scheduling (MS).
Pinedo (2022) [2]	Defined MS within Manufacturing Planning and Control (MPC); identified scheduling as NP-hard.
Baker & Trietsche (2009) [4]	Characterized MS as a decision-making process focused on resource distribution and optimization.
Zijm & Kals (1995); Shen, Wang & Hao (2006) [5]	Addressed MS as a complex, combinatorial, NP-hard problem and integrated problem, namely occurring in distributed manufacturing environments, solvable, for instance, via heuristics/ meta-heuristics, and agent-based approaches.
Madureira, Ramos & Carmo-Silva (2003) [7]	Discussed real-time scheduling/rescheduling due to unexpected disruptions on the shop floor.
Goren & Sabuncuoglu (2008); Ouelhadj & Petrovic (2009) [8]	Stressed the need for dynamic scheduling to cope with real-time changes.
Aytug et al. (2005) [10]	Proposed classification of dynamic scheduling: Reactive, Predictive-Reactive, Proactive.
Vieira, Varela & Putnik (2012) [11]	Outlined various scheduling methods including priority rules, mathematical models, simulation.
Wang, Shen & Shen (2002); Ramakurthi et al. (2021) [12, 13]	Proposed use of multi-agent and collaborative learning based systems for manufacturing scheduling.
Varela et al. (2019) [14]	Emphasized importance of Integrated Production and Maintenance Scheduling (IPMS) in Industry 4.0.
Azevedo, Montaño-Vega, Varela & Pereira (2022); Varela et al. (2022, 2023); Li et al. (2018) [15-18]	Advocated collaborative, intelligent, decentralized scheduling using HPC.
Ladj, Varnier & Tayeb (2016); Biondi, Sand & Harjunkoski (2017); Modekurthy, Saifullah, Madria (2021); Zhai, Gehring, Reinhart (2021) [19-22]	Contributed to integrated production and maintenance scheduling research.
Yang & Takakuwa (2017); Varela et al. (2022a); Ferreirinha et al. (2019); Hofer et al. (2020); Alves, Putnik & Varela (2021); Ebufegha & Li (2021); Varela et al. (2021,	Developed dynamic/ real-time planning and scheduling strategies.

2022) [16, 23-29]	
Sousa & Oliveira (2024); D'Aniello, Modekurthy, Saifullah, Madria (2021) [30, 31]	Investigated decentralized and distributed scheduling methods.
Kalinowski et al. (2013); Jimenez et al. (2016); Cardin et al. (2017); Morariu et al. (2020); Putnik et al. (2021); Samala et al. (2021); Tighazoui et al. (2021); Wenzelburger & Allgöwer (2021 Azevedo, Montaño-Vega, Varela & Pereira (2022) [32-40]	Focused on AI-based, intelligent, predictive scheduling within Industry 4.0.
Santos, Madureira & Varela (2015); Sequeiros et al. (2021); Sousa et al. (2021); Santos, Costa & Varela (2022); Moreira et al. (2023); Sousa et al. (2023); Silva et al. (2023) [41-47]	Proposed and applied various heuristic and meta-heuristic approaches for MS.

3. Integrated manufacturing management platform

In this paper, it is intended to briefly present the developed IMMP, which was put available in a networked Company interacting with a set of stakeholders, at internal and external levels.
The general IMMP's architecture through which it was implemented and put available, as an industrial solution, in the extended Company considered in this study, where it was validated.
The general objective reported consisted on enabling integrating maintenance and manufacturing information and its further processing, by using the following three main modules of the corresponding HRS of the CP:

(i) pre-processing module, for manufacturing and maintenance data processing, including data normalization, uncertainty treatment, prioritization, and further joint processing;
(ii) central or core module, for carrying out integrated, dynamic and intelligent manufacturing and maintenance orders scheduling:
(iii) post-processing module, for enabling further manufacturing and maintenance information monitoring and analysis.

The IMMP put available through the central or core module, is based on an underlying extended collaborative manufacturing scheduling model [23, 48, 49], which does include sub models for permitting the decomposition of complex integrated manufacturing and management information arising from production orders, along with the information related to the maintenance tasks, aiming at its further joint scheduling.

Therefore, problems are initially spread into simpler ones, based on an hybrid architecture, and further based on the use of appropriated scheduling algorithms, varying from more traditional and pure mathematical programming methods up to varying kind of heuristics, meta-heuristics and other AI-based approaches, namely based on machine/ deep learning (M/DL) [36].

Moreover, the IMMP uses diverse data sets that were obtained from the main Company's historical data repository, and subsequently, acquired in a real time basis, and dynamically gathered at the company's manufacturing units or work centres, including manufacturing and maintenance information, among other data from the involved stakeholders.

Besides, another fundamental IMMP's module enables manufacturing and maintenance data pre-processing, normalization, and corresponding tasks prioritization, which is carried out through an adapted multi-criteria decision method, along with uncertainty and incomplete data processing, and data fusion approaches, along with encompassing data forecasting methods, also based on a dynamic model [50]. As a result, this module of the IMMP enables to classify and to establish priorities and rankings about manufacturing orders and maintenance tasks, for the further joint data processing, namely for the integrated scheduling of these orders and tasks, carried out through the IMMP's core or central module, which, in turn, includes a Hybrid Recommender System (HRS).

An additional data post-processing and analysis module focuses on further data curation and analysis, to enable subsequent recommendation of future and improvement actions regarding the joint processing and analysis of manufacturing orders and maintenance tasks management, through cloud based IaaS/ PaaS that enable the full IMMP functionalities, alongside with required intangible assets, with a special focus on dynamic big data acquisition and processing [29], arising from the companies' main manufacturing system, along with the associated factories and stakeholders, by further permitting a collaborative and 'learning factory' based environment [16, 17, 23, 48], also put available through the developed platform.

The dynamic contents put available through the IMMP allows an incremental and automatic update by all authorized users, along with the possibility to update and integrate new devices, tools and dashboards. This part makes it possible to fulfil the transfer of knowledge and its digitization.

3.1. Main hardware and software

In this section a general overview on the main hardware and software of the developed collaborative platform and underlying systems is provided, which include general and local management tools, not just a the global or overall platform's use, but also regarding the local management systems used at each companies work centre, by using corresponding pre, core and post processing modules.

The Collaborative management system's hardware and software, including interfaces for integrated data pre, core, and post processing.

The developed collaborative management platform is divided in four main systems, for enabling data processing at different levels, through the developed pre, core and post-processing modules, as follows:

- a global general management and information processing module;
- a global locally instantiated management (integrated maintenance tasks and production orders scheduling) module;
- a global locally instantiated general planning, monitoring and controlling module;
- a local planning, monitoring and controlling module, based on smart objects and other technology.

This modules are briefly presented in the next sections, including some main functionalities that come from the use of smart objects (smart objects or boxes), along with other input and output devices mainly to support controlling production activity, on the factory floor level (local plants or work centres), through functions to control the work in progress.

Hardware/ Functionalities

- Serial Communication, Ethernet, USB, Wi-Fi, among others;
- Inputs to connect different types of sensors;
- Outputs to connect different actuators;
- Connection to the central database;
- Listing of various types of information, such as: errors, anomalies, alarms, production, notes, maintenance, among others;
- Measurement of electrical consumption;
- Integration with other technologies, barcode readers, cameras, RFID (Radio Frequency Identification);
- Others ...

The developed IMMP includes different kind of input and output devices, namely two kind of boxes, called IndustBox-Slave and IndustBox-Master that were tested through the pilot installation in the considered Company, and underlying factories and work centres, enabling connection with suppliers and customers, besides the associated business partners, once they did reveal interest in being connected and communicating through the developed platform, by showing total availability to collaborate in the tests and validation of the obtained results. In this study, the work centres involved reflect their business and innovation strategy in the light of this project whose application assumes the Planning, Control and Monitoring of all industrial activity, to detect threats and opportunities for the businesses of SMEs. This validation will allow refining the products and making fine adjustments leading to the production of the final versions. The pilot implementation study is expected to last until the end of the project, for a total of around 8 months, including the past 2 months followed by additional 6 months for adjustments that emerge as necessary.

The IMMP was implemented by previously exploring alternative architectures, varying from centralized up to fully P2P, and the final implemented solution consists on a hybrid architecture, as it benefits from several benefits, requirements and implications, for instance regarding the complexity inherent to the use of the P2P architecture and the lack of integration and interoperation capabilities associated to the centralized architecture.

A pilot implementation study conducted at the Company were the IMMP was implemented did enable to realize that this platform enables and properly supports the integration of manufacturing managements processes among collaboration stakeholders in joint management decision-making. Thus, based on the hybrid architecture developed and implemented it was possible to properly support joint manufacturing management decision-making among a set of Company's stakeholders involved, namely regarding integrated manufacturing orders and maintenance tasks planning and scheduling. The IMMP implemented brings important benefits to the networked company compared to the previous centralized one, for instance regarding the additional ability to validate a general planning and scheduling solution, for the whole set of participating production centres considered in the company. Thus, the use of the proposed hybrid architecture has shown to be very useful for ensuring overall objectives of the main company and associated work centres, by considering not just internal and external production measures, but further maintenance related ones, in a fully integrated processing and joint evaluation process that further considers local stakeholder's objectives.
Further the IMMP is being put available as cloud based IaaS/ PaaS, enabling big data processing and analysis in a real time basis, and further based on learning factory paradigm, to enable and promote collaboration among the networked company's stakeholders.

3.2. Platform illustration

The integrated manufacturing management platform (IMMP) includes different kind of software tools (systems) to enable general global and local management, through appropriate modules developed to enable pre, core, and post processing of data, at each factory's work centre, besides the general global management companies' functions.

The IMMP included a set of main modules regarding integrated global and local stakeholders objectives satisfaction management processed and underlying tools that will be briefly mentioned and presented.

Some of the main functionalities that are put available through the IMMP through the corresponding interfaces permit access to several tools, namely to carry out joint: (1) general manufacturing planning, monitoring and controlling; (2) manufacturing orders and maintenance tasks planning and scheduling; (3) maintenance planning; and (4) other local planning, monitoring, and controlling functions, based on diverse technology, including smart objects and dashboards, all regarding its use at each factory or work centre associated to the main Company in a networked or extended manufacturing environment.

One important aspect is the possibility to share, process, analyse and jointly decide, based on real time data, put available through the whole set of stakeholders involved in the Company, further enabling automatic and dynamic data updating of the information used and presented through the developed platform.

In the Figure 1 a general platform's stakeholder authentication interface is shown.

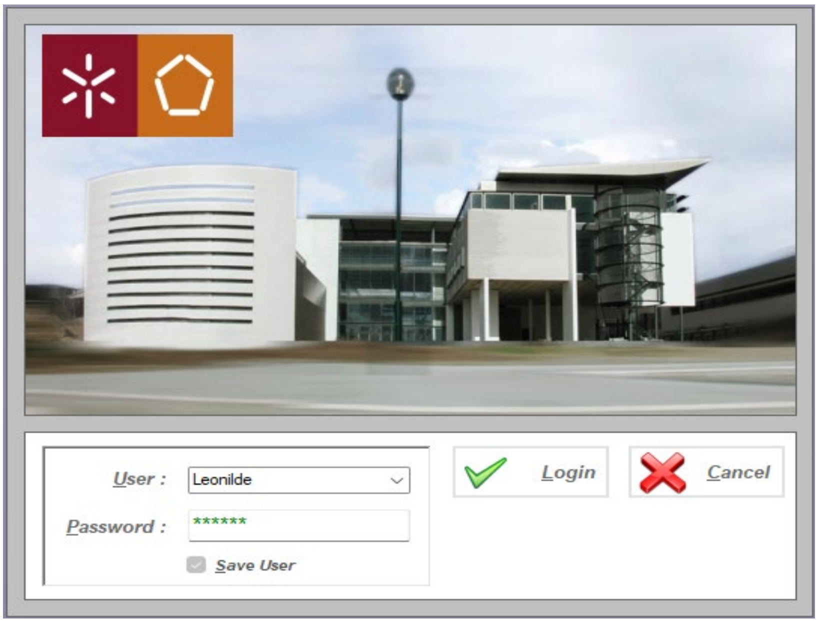

Figure 1. Platform's stakeholder authentication interface

Another interface though which a more or less widened set of participating entities (e.g. factories or manufacturing centres) can access a set of tools for enabling integrated manufacturing orders and maintenance task scheduling is illustrated in Figure 2.
The IMMP does also include a set of main functionalities, focusing, among others, on the following issues:

(1) local manufacturing units and underlying resources planning, monitoring and controlling, and (2) additional functionalities through the use of smart objects (boxes), which allows locally acquiring, viewing and processing information from a given context or manufacturing unit or work centres associated to the corresponding factories.

The IMMP does further enable access to other kind of systems and tools, for instance to local systems that permit supporting planning and scheduling at each factory or work center, and the Figure 2 illustrates an interface through which the users can access to a set of tools for processing maintenance and production orders information, by using different kind of approaches and algorithms for different purposes, for instance to access and process past or historical, namely for further predicting data to properly recommend maintenance services according to a set of local and global company's objectives, based on machine learning (ML) algorithms, along with MCDM.

One of the platform's tools enables supporting joint manufacturing orders and maintenance tasks planning and scheduling, through specific functionalities that permit accessing and processing past or historical data at each local factory (work center) among other functionalities, for instance to treat uncertainty and process incomplete information. Also data filtering, weighting and fusion, based on different kind of approaches and methods is possible, namely by using dynamic multi-criteria decision method (DMCDM) for data ranking and joint processing, among the different stakeholders or collaborators from the different factories or work centres.

In a similar way, it is also possible to process present or current data, arising from the different factories or work centres, for instance through real time data acquisition by using diverse kind of technology locally available at each location, namely based on RFID, smart objects and other technology, devices and appropriate dashboards.

There are also other specific interfaces, for instance to enable data normalization, uncertainty treatment and fuzzification, along with the assignment of weights, and data fusion, regarding current or present data acquired at each factory of work center.

The local software tools do further enable future data processing can be based on different kind of methods, for instance based on diverse kind of forecasting methods, along with other kind of approaches and algorithms, namely based on ML techniques.

Another important functionality that is put available through the local software tools is related to the data fusion, regarding not just the fusion of past, present and future data arising locally, at each factory or work center, but further regarding the overall data fusion process to dynamically aggregate, process and rank data arising from each location, namely about maintenance data processing and corresponding task prioritization, based on appropriate dynamic multi-criteria decision methods (Figure 2).

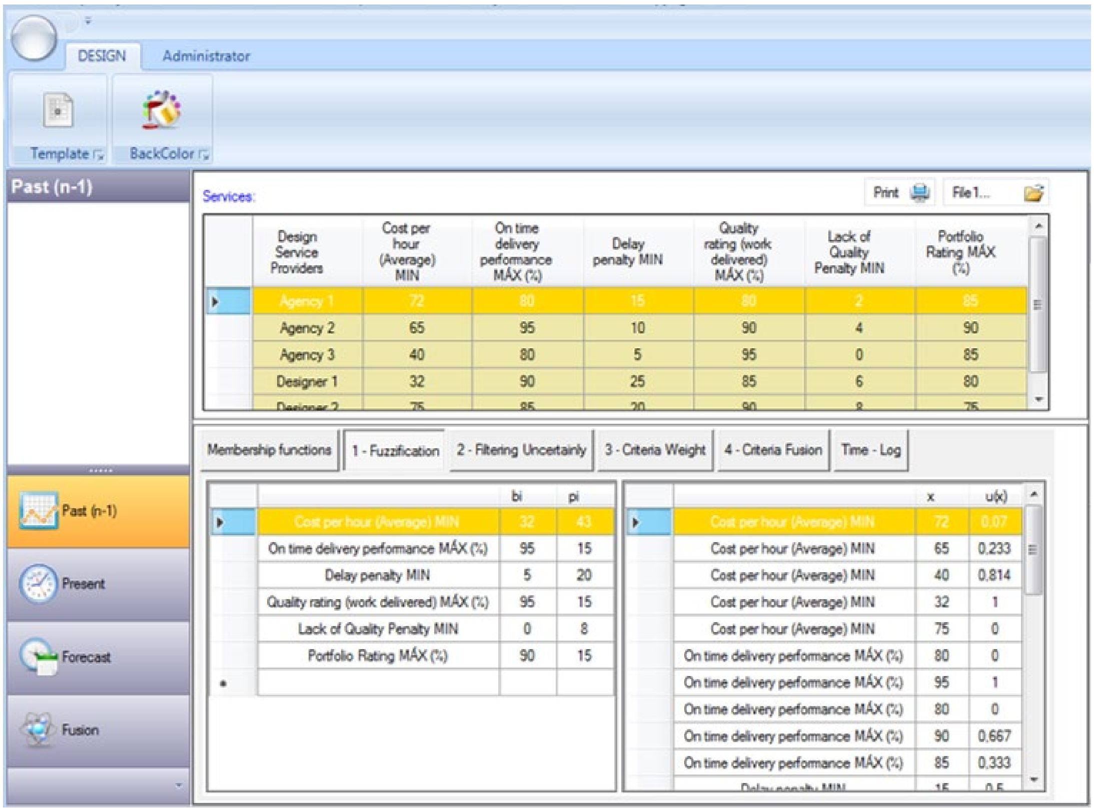

Figure 2. Platform’s integrated manufacturing and maintenance tasks planning interface

At each factory or work center, there are also local systems available that permit different kind of other functionalities to support maintenance tasks and production orders processing. One such functionality is related to the registration of all types of machines, for instance at a sewing section, along with the possibility of acquiring, processing and analysing data from these machines, in a real-time basis, by using smart objects.

Smart objects (SO) or ‘boxes’ (electronic devices with LCD Tablet type) are an exclusive product of a hardware and software development company, using the latest and innovative technology.

The SO are connected to sensors that enable acquiring signals from the various types of machines installed in the company (at each factory or work center), transforming these signals into information on the intelligent integrated platform, which configures an Intelligent Decision Support Tool (IDST). These SO enable, for instance, replacing traditional peace's counting methods by advanced tools, once the traditional tools and counting methods have been proving to be inefficient due to the production process being increasingly demanding and constantly changing, while production deadlines are becoming increasingly shorter and strict.

The proposed IMMP enforces a dynamic interoperability architecture to enable integrated heterogeneous manufacturing systems with plug-and-play interoperability, a co-optimization engine to attain simultaneous production maintenance schedules (end up reducing the conflicts by ~40% to ~60%, a knowledge propagation engine based on AI that reduces MTTR by ~35%, which shows measurable positive impact on scalability and decision making efficiency compared to conventional MES/ ERP solutions.

Moreover, the proposed IMMP delivers transformative impact through three breakthrough innovations: (1) its flexible middleware architecture achieves 92% faster system integration compared to traditional MES solutions, (2) a common hybrid digital twin/RL optimization engine increases device effectiveness by up to 28% in test deployments, and (3) a federated learning framework enables knowledge transfer across factors while maintaining 99.7% data security compliance – collectively.

4. Discussion

In this paper a platform for enabling integrated manufacturing management processes (IMMP) was briefly presented, which includes three main modules:

- A pre-reprocessing module: data acquisition, along with normalization techniques, multi-criteria methods, data fusion approach, and uncertain and/or incomplete data treatment, and the use of multivariate data sets for analysis.
- A core module: for the integrated dynamic scheduling, based on AI-based approaches.
- A post-processing module: data visualization, through the specification of appropriate collaborative interfaces and procedures for data post-processing, monitoring, and analysis in the context of PAC.

The IMMP was implemented in a networked Company integrating a set of participating stakeholders, and its validation was carried out through its real-world application and test evidence.
In a first development phase, the IMMP has considered just a local Maintenance Orders planning tool through a group of Company's stakeholders, to reach out some main maintenance processes and tools needed across the whole company's users. These local software solutions were discussed among the set of global and local Company's participants and users.
Afterwards, according to the first user's tools evaluation results analysis a final prototype was tested, along with the new underlying functionalities and the previous ones that were also improved, as the goal was to make available a fully integrated and dynamic data processing and decision support system through the IMMP, namely to support integrated manufacturing orders and maintenance tasks planning and scheduling across the Company's stakeholders.
According to the new results obtained it was possible to realize that the developed IMMS was ready for being implemented in the Company, as all stakeholders did agree that it was a fundamental step forward towards reaching a proper platform to carry out fundamental joint manufacturing management decision making. One important issue is about the importance of the associated software tools that permit enabling access to shared information and fundamental integrated processes through appropriated procedures to jointly manage production orders and maintenance tasks.

In this regard, two main answers, and underlying suggestions were given by the stakeholders, as follows:

1 "There are some complex aspects for using the systems, and not just anyone can handle them. However, while there may be some challenging points initially, with regular use, it will become easier to navigate and utilize the software tools."

2 "Here are some suggestions:

- Voice commands can help improve usability.
- Having the location tree of the tools available through a main shared structure, starting with reading a QR code from a system, and allowing technicians to navigate to a more detailed level. Reading the QR code directly from the asset on the plant (factory/ work center) may be difficult due to the small size of the label.
- Integrating the tools with others put locally available at each factory of work center would be highly beneficial. For example, reading the QR code and allowing users to view maintenance plans for that asset (open, overdue, last executed). This would enable users to perform a Gemba walk and instantly access the maintenance status of equipment in terms of maintenance strategy. This point holds great potential for supervisors and maintenance managers during their daily Gemba walks."

The participants that interacted by using the platform's solutions commands recognized considerable advantages of using it.
Also, unanimity on the value of the interfaces regarding the global and local management support systems (solutions).

Two answers were given:
1. “Interfaces are indeed typically given in English, which can be challenging for technicians who have difficulty with the language. However, in this case, since the dashboards are easy to understand and manage, they are in general easily handled and valuable for the user, especially the ones that enable quickly reach and process information, including historical, current and provisional data.”
2. “Some commands, regarding specific local functionalities, regarding each factory/ work center were not fully tested.”
Everyone agreed that the implementation method supported by appropriate data, including images, videos, pdf files, among other multimedia files enable reinforcing the general management and decision-making processes at the Company’s main factory along with the associated factories and stakeholders. Thus, everyone agreed about the importance of the developed pre and post data processing modules that are integrated in the developed platform, through the underlying core or central module, to support integrated and joint maintenance and production management, by including functionalities for data pre-processing, namely about data filtering, uncertainty treatment, data fuzzification, along with data visualization, analysis and post processing, to further enable proper production monitoring and control at each local work center.
In the direct responses, the evaluations are positive, which puts into question whether the tests were conducted under ideal conditions. It was also denoted some apprehension regarding the possibility of the IMMP along with the associated systems and technology being implemented in the maintenance and production management department could conduct to a reduction in human resources.
Although, overall the appreciation of the IMMP developed and the underlying software tools and technology by the stakeholders involved on each evaluation was positive regarding the main processes integrated so far, about the general or overall and local maintenance and production management decision-making support team.

5. Conclusion

This paper refers to an overall presentation and the IMMP developed and implemented in a company and collaborating stakeholders, regarding its general purpose and architecture, along with some main underlying modules and associated systems, for carrying out the envisioned integrated manufacturing management in the networked Company, by presenting some main characteristics and benefits, along with some further developments for future exploration. One main issue regarding the use of innovative technology regarding hardware and software is about the need of satisfying not just global Company’s manufacturing management goals but further local stakeholders’ ones to permit a fully integrated and joint decision making. One such needs occurs in terms of joint production orders and maintenance tasks planning and scheduling, which is a main focus in this paper, along with other fundamental management functions to be performed in an industrial environment.
The IMMP is prepared to dynamically consume the information that is considered relevant, either manually and/or automatically, and in a real time basis, through the use of smart objects (boxes), put available at each factory/ work center, with a lower effort rate.

A set of progressive improvements carried out on the developed platform did enable to better and increasingly attend to the user needs, according on the feedback obtained through their experience, which has improved satisfaction rate in using the underlying systems put available through the platform.

Thus, overall, it was denoted that there has been a positive evolution of the platform and a convergence in terms of the satisfaction of diverse needs arising not just from the main Company but also from the associated stakeholders.

The three main software tools or modules underlying the developed integrated platform primarily envisioned for supporting integrated production and maintenance management did further enable aiding other relevant ones, for instance to support problems diagnosis, decision-making, besides intervention planning and scheduling, along with other collaborative assistance services at the production activity control and monitoring levels, alongside with the operational level, based on a wide range of technology, including integrated smart objects and other devices and dashboards.

Further developments include the development of a maintenance configurator, in articulation with other further technology and tools, for instance a holographic tool, to capture, process and analyse additional information for supporting not just maintenance tasks but fully integrated manufacturing and management processes.
Additional implementations about integrated and intelligent manufacturing management processes are also envisioned, with a special focus on integrated manufacturing and maintenance information processing, based on alternative AI-based approaches and tools, aiming at improved intelligent decision-making and scheduling processes.
Moreover, to achieve the full goal of interoperability, the consumption of appropriate telemetry data is also a process to be considered, based on additional sensor data acquisition, to improve the knowledge for the end-user. The platform will also be upgraded to permit consuming other data from third-party applications regarding each specific stakeholders’ needs, namely regarding the integration of digital twins, along with augmented and virtual, thus, mixed reality technology integrated with the developed platform.

Other important issues to be explored are about the need of additional collaborative manufacturing management processes and practices implementation in the current Industry 4.0 context, along with the consideration of additional sustainability concerns. In this regard, integrating extra modules and associated technology and tools for promoting and enabling a sustainable development of companies is also a further main goal.

Acknowledgements

This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the R&D Unit Project of ALGORITMI Centre.

References

[1] Lopes, N., Costa, B., Alves, C.F., Putnik, G. D., Varela, M.L.R., Cruz-Cunha, M. M., Ferreira, L. (2022).The Impact of Technological Implementation Decisions on Job-Shop Scheduling Simulator Performance using Secondary Storage and Parallel Processing. 1st International Symposium on Industrial Engineering and Automation (ISIEA 2022), Managing and Implementing the Digital Transformation, 21st-22nd June 2022, Bozen-Bolzano, Italy. Lecture Notes in Networks and Systems (pp. 227-236), Springer.

[2] Pinedo, M. L. (2022). *Scheduling: Theory, Algorithms, and Systems* (6th ed.). Springer.

[3] Pinedo, M., & Chao, X. (1999). Operations scheduling with applications in manufacturing and services.

[4] Baker, K.R.; Trietsch, D. Safe scheduling: Setting due dates in single-machine problems. Eur. J. Oper. Res. 2009, 196, 69–77.

[5] Zijm, W. H., & Kals, H. J. J. (1995). The integration of process planning and shop floor scheduling in small batch part manufacturing. *CIRP annals*, 44(1), 429-432.

[6] Shen, W., Wang, L., & Hao, Q. (2006). Agent-based distributed manufacturing process planning and scheduling: a state-of-the-art survey. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 36(4), 563-577.

[7] Madureira, A.; Ramos, R.; Carmo Silva, S. Using Genetic Algorithms for Dynamic Scheduling. In Proceedings of the 14th Annual Production and Operations Management Society Conference (POMS'2003), Savannah, GA, USA, 4–7 April 2003.

[8] Goren, S.; Sabuncuoglu, I. Robustness and Stability Measures for Scheduling: Single Machine Environments. IIE Trans. 2008, 40, 66–83.

[9] Ouelhadj, D., & Petrovic, S. (2009). A survey of dynamic scheduling in manufacturing systems. Journal of scheduling, 12, 417-431.

[10] Aytug, H.; Lawley, M.A.; McKay, K.; Mohan, S.; Uzsoy, R. Executing production schedules in the face of uncertainties: A review and some future directions. Eur. J. Oper. Res. 2005, 161, 86–110.

[11] Vieira, G., Varela, M. L. R., Putnik, G. D. (2012). Technologies Integration for Distributed Manufacturing Scheduling in a Virtual Enterprise. Putnik, GD; Cruz-Cunha, MM (Ed.). 1st International Conference on Virtual and Networked Organizations Emergent Technologies and Tools (ViNOrg 2011). Communications in Computer and Information Science. Vol. 248, 337-347.

[12] Wang, D., Shen, R., & Shen, L. (2002). Collaborative learning based on multi-agent model. In Web-Based Learning: Men And Machines (pp. 107-114).

[13] Ramakurthi, V. B., Manupati, V. K., Machado, J., & Varela, M. L. R. (2021). A hybrid multi-objective evolutionary algorithm-based semantic foundation for sustainable distributed manufacturing systems. Applied Sciences, 11(14), 6314. MDPI, Switzerland. https://doi.org/10.3390/app11146314.

[14] Varela, M.L.R. (2019). An Industry 4.0 oriented tool for supporting dynamic selection of dispatching rules based on Kano model satisfaction scheduling. FME Transactions. 47, 757–764.

[15] Azevedo, B.F.; Varela, M.L.R.; Pereira, A.I. Production Scheduling Using Multi-objective Optimization and Cluster Approaches. In Proceedings of the International Conference on Innovations in Bio-Inspired Computing and Applications, Online, 16–18December 2021; pp. 120–129.

[16] Varela, M. L. R., Putnik, G.D., Romero, F. (2022). The Concept of Collaborative Engineering: a Systematic Literature Review. Production & Manufacturing Research, 10(1), 784-839, Taylor & Francis, https://doi.org/10.1080/21693277.2022.2133856

[17] Varela, M. L. R., Trojanowska, J., Cruz-Cunha, M. M., Pereira, M. A., Putnik. G. D., Machado, J. (2023). Global Resources Management: A Systematic Review and Framework Proposal for Collaborative Management of CPPS, *Applied Sciences*, 13, 750, 1-19, MDPI, Swizerland. Doi: 10.3390/app13020750.

[18] Li, L. China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0".Technol. Forecast. Soc.Chang.2018, 135, 66–74.

[19] Ladj, A., Varnier, C., & Tayeb, F. B. S. (2016). IPro-GA: an integrated prognostic based GA for scheduling jobs and predictive maintenance in a single multifunctional machine. IFAC-PapersOnLine, 49(12), 1821-1826.

[20] Biondi, M., Sand, G., & Harjunkoski, I. (2017). Optimization of multipurpose process plant operations: A multi-time-scale maintenance and production scheduling approach. Computers & Chemical Engineering, 99, 325-339.

[21] Modekurthy, V. P., Saifullah, A., & Madria, S. (2021). A distributed real-time scheduling system for industrial wireless networks. ACM Transactions on Embedded Computing Systems (TECS), 20(5), 1-28.

[22] Zhai, S., Gehring, B., & Reinhart, G. (2021). Enabling predictive maintenance integrated production scheduling by operation-specific health prognostics with generative deep learning. Journal of Manufacturing Systems, 61, 830-855.

[23] Varela, M. L. R., Ávila, P., Castro, H., Putnik, G. D., Fonseca, L.M.C., & Ferreira, L. (Editors) (2022a). Manufacturing and Management Paradigms, Methods and Tools for Sustainable Industry 4.0-Oriented Manufacturing Systems (Editorial). *Sustainability*. 14, 1574 (2022), MDPI. https://doi.org/10.3390/su14031574.

[24] Yang, W. H., & Takakuwa, S. (2017). Modeling and analysis of the customer checkout process with flexible servers for a retail store. In Proceedings of the 23rd International Conference on Industrial Engineering and Engineering Management 2016: Theory and Application of Industrial Engineering (pp. 301-304). Atlantis Press.

[25] Ferreirinha, L., Santos, A. S., Madureira, A. M., Varela, M. L. R., & Bastos, J. A. (2020). Decision support tool for dynamic scheduling. In Hybrid Intelligent Systems: 18th International Conference on Hybrid Intelligent Systems

(HIS 2018) Held in Porto, Portugal, December 13-15, 2018 18 (pp. 418-427). Springer International Publishing.

[26] Hofer, F., Sehr, M. A., Russo, B., & Sangiovanni-Vincentelli, A. (2020, May). ODRE workshop: Probabilistic dynamic hard real-time scheduling in HPC. In 2020 IEEE 23rd International Symposium on Real-Time Distributed Computing (ISORC) (pp. 207-212). IEEE.

[27] Alves, C., Putnik, G.D., Varela, M.L.R. (2021). How environment dynamics affects production scheduling: Requirements for development of CPPS models. FME Transactions. 49, 827–834.

[28] Ebufegha, A., Li, S. (2021). Multi-agent system model for dynamic scheduling in flexibile job shops. In: 2021 Winter Simulation Conference (WSC). pp. 1–12 (2021).

[29] Varela, M. L. R., Putnik, G. D., Manupati, V. K., Rajyalakshmi, G., Trojanowska, J., & Machado, J. (2021). Integrated process planning and scheduling in networked manufacturing systems for I4.0: a review and framework proposal. Wireless Networks, 27(3), 1587-1599. DOI: 10.1007/s11276-019-02082-8.

[30] de Sousa Oliveira, P., de Oliveira, M. T. B., Oliveira, E., Conceição, L. R., Marcato, A. L. M., Junqueira, G. S., & de Alencar Junior, C. A. V. (2021). Maintenance schedule optimization applied to large hydroelectric plants: Towards a methodology encompassing regulatory aspects. IEEE Access, 9, 29883-29894.

[31] D'Aniello, G., De Falco, M., Mastrandrea, N. (2021). Designing a multi-agent system architecture for managing distributed operations within cloud manufacturing. 14, 2051–2058.

[32] Kalinowski, K., Krenczyk, D., Grabowik, C. (2013). Predictive-reactive strategy for real time scheduling of manufacturing systems. In Applied Mechanics and Materials. 307, 470–473 (2013).

[33] Jimenez, J.F., Bekrar, A., Trentesaux, D., Leitão, P. (2016). A switching mechanism framework for optimal coupling of predictive scheduling and reactive control in manufacturing hybrid control architectures. International Journal of Production Research. 54, 7027–7042 (2016).

[34] Cardin, O., Trentesaux, D., Thomas, A., Castagna, P., Berger, T., Bril El-Haouzi, H. (2021). Coupling predictive scheduling and reactive control in manufacturing hybrid control architectures: state of the art and future challenges. Journal of Intelligent Manufacturing. 28, 1503–1517.

[35] Morariu, C., Morariu, O., Răileanu, S., & Borangiu, T. (2020). Machine learning for predictive scheduling and resource allocation in large scale manufacturing systems. Computers in Industry, 120, 103244.

[36] Putnik. G.D., Pabba, S.K., Manupati, V. K., Varela, M. L. R., Ferreira, F. (2021), semi-Double-loop machine learning based CPS approach for predictive maintenance in manufacturing system based on machine status indications, *CIRP Annals - Manufacturing Technology*, 70(1), 365-368. Elsevier, Netherlands. ISSN 0007-8506. https://doi.org/10.1016/j.cirp.2021.04.046

[37] Samala, T., Manupati, V. K., Nikhilesh, B. B. S., Varela, M. L. R., & Putnik, G. (2021). Job adjustment strategy for predictive maintenance in semi-fully flexible systems based on machine health status. *Sustainability*, 13(9), 5295.

[38] Tighazoui, A., Sauvey, C., & Sauer, N. (2021). Predictive-reactive strategy for identical parallel machine rescheduling. Computers & Operations Research, 134, 105372.

[39] Wenzelburger, P., & Allgöwer, F. (2021). Model predictive control for flexible job shop scheduling in industry 4.0. Applied Sciences, 11(17), 8145.

[40] Azevedo, B. F.; Montaño-Vega, R.; Varela, M. L. R.; Pereira, A. I. (2022). Bio-inspired Multi-objective Algorithms Applied on Production Scheduling Problems (2022). *International Journal of Industrial Engineering Computations*, 6(2), 145-156. Growing Science, Canada. Doi: 10.5267/j.ijiec.2022.12.001

[41] Santos, A. S., Madureira, A. M., & Varela, M. L. R. (2015). An ordered heuristic for the allocation of resources in unrelated parallel-machines.

[42] Sequeiros J.A., Silva R., Santos A.S., Bastos J., Varela M.L.R., Madureira A.M. (2021). A Novel Discrete Particle Swarm Optimization Algorithm for the Travelling Salesman Problems. In: Machado J., Soares F., Trojanowska J., Ivanov V. (eds). Innovations in Industrial Engineering, (ICIE 2021), Lecture Notes in Mechanical Engineering. Vol.3, pp. 48-55, Springer. https://doi.org/10.1007/978-3-030-78170-5_5.

[43] De Sousa, A. L., & De Oliveira, A. S. (2024). Scheduler with Buffer and Transportation Constraints for Inserting Rush Orders Without Deadlocks During Agent Convergence. IEEE Access.

[44] Santos, F., Costa, L., Varela, M.L.R. (2022). A Systematic Literature Review about Multi-objective Optimization for Distributed Manufacturing Scheduling in the Industry 4.0. In Proceedings of the 22nd International Conference on Computational Science and Its Applications (ICCSA 2022), Osvaldo Gervasi, Beniamino Murgante, Sanjay Misra, Ana Maria A.C. Rocha, Chiara Garau (Eds.), Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. *Lecture Notes in Computer Science*, vol 13378 (pp. 157-173), Springer. https://doi.org/10.1007/978-3-031-10562-3_12

[45] Moreira, C., Costa, C., Santos, A.S., Bastos, J.A., Varela, M.L.R., Brito, M.F. (2023). Firefly and Cuckoo Search Algorithm for Scheduling Problems: A Perfomance Analysis. In: Innovations in Mechatronics Engineering II. icieng 2022. Lecture Notes in Mechanical Engineering (pp. 75-88) Springer.

[46] Sousa, B., Guerreiro, R., Santos, A.S., Bastos, J.A., Varela, M.L.R., Brito, M.F. (2023). Bat Algorithm for Discrete Optimization Problems: An Analysis. In: Innovations in Mechatronics Engineering II. icieng 2022. Lecture Notes in Mechanical Engineering (pp. 161-172), Springer. https://doi.org/10.1007/978-3-031-09382-1_14.

[47] Silva, J. C., Lopes, N., Alves, C., Putnik, G., Varela, L., Ferreira, L., & Cruz-Cunha, M. (2023). Evaluation of Solvers' Performance for Solving the Flexible Job-Shop Scheduling Problem. Procedia Computer Science, 219, 1043-1048.

[48] Varela, M. L. R.; Alves, C.F.V.; Santos, A.S.; Vieira, G.G.; Lopes, N.; Putnik, G.D. Analysis of a Collaborative Scheduling Model Applied in a Job Shop Manufacturing Environment (2022b). *Machines*, MDPI, 10(12), 1138, 1-16, https://doi.org/10.3390/machines10121138.

[49] Varela, M. L. R., Putnik, G.D., Alves, C.F., Lopes, N., Cruz-Cunha, M.M. (2022c). A Systematic Review of Manufacturing Scheduling for the Industry 4.0. 1st International Symposium on Industrial Engineering and Automation (ISIEA 2022), Managing and Implementing the Digital Transformation, 21st-22nd June 2022, Bozen-Bolzano, Italy. *Lecture Notes in Networks and Systems* (pp. 237-249), Springer.

[50] Varela, L., Putnik, G., Vieira, G., Manupati, V., & Alves, C. (2024). Group Decision Making Approach for Ranking and Selecting Maintenance Tasks for Joint Scheduling with

Production Orders. *International Journal for Quality Research*, 18(1).