Including energy saving in planning and scheduling. A case study

Bertolini M., Galli M., Mezzogori D., Neroni M.

"Enzo Ferrari" Engineering Department, University of Modena and Reggio Emilia, Via P. Vivarelli, 10 - 41125 Modena – Italy (massimo.bertolini@unimore.it; matteo.galli@unimore.it; davide.mezzogori@unimore.it; mattia.neroni@unimore.it)

Abstract: Production processes consume more natural resources than is ecologically bearable, motivating environmental policies to emphasize the efficient consumption of renewable resources. A key issue in manufacturing is how to optimize processes to produce more with less energy, reducing overall costs and contributing to a green economy. Although most of the energy efficiency gains are achieved through more efficient machines and plants, a significant part of the energy savings can be achieved through optimized production and scheduling plans. Industrial companies plan their production considering many variables, but often neglect those related to energy availability and costs. This paper will address this issue through the design and test of an advanced planning and scheduling system for a manufacturing company. The planning and operation of energy-efficient production systems require the integration of the company's energy management systems and production scheduling, analysing the energy consumption behaviour of components and production processes, and designing optimization methods to deal with different scenarios. In particular, we will develop an optimization model for planning and scheduling operations based on the analysis of a combination of energy availability, costs and consumption patterns, and operational problems.

Keywords: Energy consumption; Scheduling, Manufacturing planning; Advanced planning and scheduling

I. INTRODUCTION

The manufacturing and assembly activities of manufacturing companies, as well as the distribution logistics of goods, are considered to be among the main contributors to climate-altering gas emissions and primary energy consumption (Beamon, 1999). It is estimated that net anthropogenic greenhouse gas (GHG) emissions globally from 2010 to 2019 were higher than any other period in human history. Since 2010, uninterruptedly, emissions in the industry, construction and transportation sectors continue to grow; emissions from these sectors account for 44% of global GHG emissions (IPCC, 2021).

Initiatives to address climate challenges have, until recently, mainly been investments referred to as "business-as-usual", but without their contribution approaching what is perceived as adequate. According to the World Economic Forum, new approaches are needed to create and ensure economic, social and environmental sustainability shortly (World Economic Forum, 2022).

In this context, 17 Sustainable Development Goals (SDGs) were recently defined by the United Nations Organization as a strategy to achieve a better and more sustainable future for all (Unites Nations, 2015). The goals, also known as the 2030 Agenda, aim to address a wide range of economic and social development issues, which include poverty, hunger, the right to health and education, access to water and energy, jobs, inclusive and sustainable economic growth, climate change and environmental protection, urbanization, production and consumption patterns, social and gender equality, and justice and peace.

The industrial system is also called upon to play its part in addressing these challenges; therefore, it is necessary to review the production philosophies and tools used to manage manufacturing enterprises (Beamon, 1999; De Burgos Jiménez and Lorente, 2001). Manufacturing systems must find ways to combine in a growth perspective economic competitiveness and environmental/social sustainability (Srivastava, 2007).

This entails a change in the way production systems are managed and thus a revision of principles and techniques on how to achieve one or more of their management objectives. Historically, management paradigms and production philosophies have changed in conjunction with the development of new technologies. Around 1890 the scientific management approach was born with Taylor and in the years immediately following the concepts of truly interchangeable parts and moving assembly lines with parts fabrication evolved into the mass production paradigm of Henry Ford (Hopp and Spearman, 2011). A few years later the philosophies of Just-in-Time or Toyota production System evolved into the lean thinking and lean enterprise of today and took hold (Womack et al., 2007)). In the 1980s total quality concepts and supply chain management of the 1990s (Srivastava, 2007). Along with the evolution of manufacturing philosophies, there was a natural progression in the way operational performance was evaluated: in the early stages of the industrial revolution, the focus was primarily on cost (Sarkis *et al.*, 2011). As competition increased, subsequent manufacturing philosophies expanded this view, describing trade-offs among what came to be called the five performance objectives: quality, speed, reliability, flexibility, and cost (Slack, 2019).

Only recently, primarily with the World Class Manufacturing approach (Flynn *et al.*, 1999), environmental issues are considered an integral part of the performance to be monitored to achieve operational excellence. New approaches to manufacturing are emerging that includes eco-efficient strategies that consume fewer materials and energy, substituting cleaner and renewable input materials, reducing unwanted outputs, and converting outputs to inputs. Awareness of the impact of production/product on the environment and implementation of ecological aspects in planning and control models are now necessary to realize ecological goals in practice.

II. THE RESEARCH PROJECT

In this paper we address the issues highlighted in the previous section (e.g., new approaches to production that include eco-efficient strategies) through the design and field testing of an advanced production planning and scheduling system. Research activities are carried out during an ongoing research project entitled "Green Advanced Planning & Scheduling" (GreenAPS) funded under the EIT Manufacturing initiative - call 2022.

Green APS aims at bringing to the market the integration of Advanced Planning and Scheduling (APS) solutions with Energy Management Systems, thus reducing the energy consumption and carbon footprint of manufacturing companies. Green APS addresses energy and production efficiency in the industry by adding energy sources and consumption variables, thus minimizing energy consumption, and maximizing the use of renewable energy sources.

As reported in the APICS Operations Management Body of Knowledge Framework, APS describes a computer program that uses advanced mathematical algorithms and logic to perform optimization or simulation to solve scheduling problems. These techniques simultaneously consider a range of constraints and business rules and provide planning, scheduling, and decision support (APICS, 2011).

Modern APS systems enable production planning and scheduling by optimizing many variables. a complete overview of APS systems can be found in Vieira et al., (2021). During the project, we will integrate within a "standard" APS (which optimizes production resource saturation and job order due date), specific requirements in terms of machine and plant energy consumption. In doing so, algorithms developed and tested, will also consider aspects of minimizing energy consumption both in the job allocation phase (e.g., with which resource to do the work on the job) and in the job scheduling phase (e.g., which job to do first and which to do next). In addition, energy-saving aspects related to manufacturing changeover (e.g., optimal changeover sequence for each machine and when to make the changeover) will be integrated by modifying – if necessary – the size of the production batch.

The field tests are conducted in two companies with extremely different characteristics, (i) a small Italian company characterized by the manufacturing of small parts with CNC and multi-spindle machines and (ii) the heat treatment department of a large Austrian group producing special steel tools.

This paper reports some considerations inherent to the experimentation conducted in the Italian company.

III. CASE STUDY

As already anticipated, this paper will address the issue of incorporating energy consumption and costs into a novel advanced planning and scheduling system for a manufacturing company. More specifically, the company in which the software will be tested is an Italian SME specialized in machining mechanical components using multi-spindle and traditional CNC machines. The company mainly sells products for hydraulic applications (catalogue production), as well as in an MTO fashion (i.e. custom requests) for machining of mechanical components for the automotive, food, construction, agriculture and hydraulic sectors. Products are characterized by a small and rather simple bill of materials (BOM). Indeed, starting from a hexagon or round bars of different metals or alloys, the main processes comprehend machining operations, metal washing, surface treatments, simple assembly (partially performed in-house and partially outsourced), and finally packaging. In-house machining operations are performed on two different types of machines, namely (i) multi-spindle machines and (ii) traditional CNC. The company operates with both Make-To-Stock (MTS) logic of catalogue production for hydraulic applications, and with Make-To-Order (MTO) logic on third-party designed products for the automotive, food, construction, agriculture, and hydraulic sectors.

The main challenges are directly related to the competitiveness of its products since the company is continuously struggling to provide flexibility to its customers. Products are constantly sampled throughout the whole production process to control costs, quality, and, in terms of volumes, production mix and delivery lead times. These challenges are directly related to the control and reduction of production costs, which are mainly associated with: (i) quality, (ii) set-up, (iii) machine starvation/undersaturation, (iv) energy and materials consumption due to rework, scrap and (v) transportation and logistics related to outsourced assembly and surface treatments. As it will be described in-depth in the following sections, all the aspects above mentioned, except for logistics costs, are deeply connected to the energy consumption and energy costs, which are nowadays more and more important to reduce.

Together with the classic challenges of maximizing throughput (e.g., items produced per unit of time) and minimizing make-span, the company also faces the challenge of maximizing its overall effectiveness (mainly the Overall Equipment Effectiveness), as a way of minimizing its Overall Industrial Costs. Although energy consumption is an important share of the overall costs sustained by the company, energy has always been considered a cost that depends solely on production volumes, and that cannot be influenced/altered by operational decisions. However, more accurate and focused control of both equipment and machines, coupled with a more sophisticated production planning and control, could shrink these costs at least in two ways: first, more efficient use of energy could be achieved considering the energy cost profile and limit energy-consuming activities when the energy cost is higher while maximizing the consumption of energy which is currently provided by photovoltaic panels. Second, but equally important, the company could also leverage the alternative cycles that can be used to manufacture a product. Most end products can be produced using alternative machines and sequences/combinations of operations, differing from one another in terms of (i) end-product quality, (ii) tools usage and wear and (iii) energy consumption. How to properly select the best alternative, depending on the current state of the job-shop system (in terms of workload and machine buffers state) and on the quality requirement of the customers, is a challenging objective that, once tackled, could have an important impact on costs and, consequently, also on the environmental sustainability of the company.

The case study aims to assess the viability and impact of a combined solution of an Advanced Planning and Scheduling system, together with an AI system capable of predicting the energy consumption of plan and schedule, ahead of time, to integrate predicted energy cost into the APS heuristic engine. Moreover, the AI system will be able to monitor the production process and alert and signal anomalous deviations from predicted production process characteristics, enabling on-time corrective actions, which will help preserve the planned schedule.

What follows is the description of the As-Is process, in particular concerning the production planning and control (PPC) phase as currently employed within the company. Finally, a description of the To-Be state of the system is thoroughly described, with emphasis on the achievable results and the main desired impact of the solution. Unfortunately, we are not currently able to disclose the results achieved, as the project is still ongoing and the KPIs are currently being measured at the time of writing.

A. As-Is

The products manufactured and marketed by the company can be either made according to customer design or made according to the company catalogue. Broadly speaking, the first case is managed in Make-To-Order (MTO) logic, the second in Make-To-Stock (MTS) logic.

The number of currently active finished product codes is between about 1,500 and 2,000. The final product is typically an assembly of a few components, typically two components, and in any case hardly more than three components. Typical components are:

- ✓ The semi-finished or raw product, made from bars of different geometry (e.g., round, hexagon) and material
- ✓ The gasket(s)
- ✓ Possible magnet

The processing cycle covers:

- ✓ Production and lathe machining
- ✓ Washing
- ✓ Surface treatment carried out externally on a contract basis
- ✓ Heat treatment
- ✓ Assembly, typically gasket assembly
- ✓ Testing
- ✓ Packaging

The company shopfloor is divided into two separate machine departments, according to the machine technology: *i)* mechanical multi-spindle machines, characterized by high productivity and high set-up times, and are generally used for large production batches; *ii)* CNC turning machines, characterized by lower productivity but also lower set-up times, generally used for small production batches. As an illustration, we proceed to describe the typical process that currently leads to the manual definition of the production schedule starting with the reception of customer orders. Once confirmed, a customer order defines *i)* the customer, *ii)* the product code requested, *iii)* the required quantity, and *iv)* the requested due date. With this information, the customer order is passed to the Production-Planning Department (PPD), and the manager chooses the machine, which will be used to satisfy the demand, according to the product turnover rate and the amount of supply required, and the saturation of the machines according to the due date. The selection of the machine is a manual process, which tries to mimic that of an RCCP algorithm, with some simplification to make it feasible to be handled manually. Specifically, the association of the production order to a particular machine is dictated by the association of the product to be manufactured and its "preferred" machine, meaning that, historically, the product is rarely scheduled to be manufactured on another machine different from the "preferred" one.

B. To-Be

As anticipated, the scope of the project is to build an enhanced APS system integrated with energy efficiency algorithms and to integrate it within the existing ERP / MRP systems. The ERP/MRP will provide necessary context information about the state of the production system (i.e. work-in-progress information, jobs to be scheduled). With the available information, the enhanced APS will provide an optimized scheduling plan which will be approved and then executed by the company MES system.

To allow for an approach to greener production planning, the APS needs to be supplemented with energy data for energy-efficient planning and scheduling. This will be conducted by an AI engine through two different data analytic processes. The first one is the energy consumption estimation. Through the collection of machine-level energy data as well as supporting data from various sources, such as the MES and the ERP, a prediction of the energy consumption per piece produced is calculated. The second one is the prediction of the energy cost, which will be calculated based on the forecast of the energy production of the company's renewable energies and the fluctuating grid energy price. With the integration of these two predictions within the heuristic optimization engine, the APS can output cost-aware and energy-efficient production plans. Finally, such an approach will enable a less constrained optimization engine, as the heuristic will be able to consider the production of a given product on more than one machine. Indeed, the hypothesis is that for a given product and all the machines that can manufacture it, there could be, for some combinations, a machine which can be more energy-efficient for that particular product. An AI-assisted green APS can leverage such information and provide a better schedule. Moreover, given the ability to generalize by the AI engine, it can infer a reliable prediction even for products whose manufacturing data is never or rarely recorded.

For the APS to analyse and return the best possible scenario, there are several data sources and connections required:

- ✓ ERP connection to retrieve all the necessary data from production orders/operations.
- ✓ Information about setup times and changeover matrices as well alternative resources for a group of selected SKUs.

To get a viable scenario, all the data needs to be as close to reality as possible. To provide energy demand and availability forecast, the AI modules have the following requirements in addition to the above-mentioned requirements of the APS:

- ✓ Installation of machine-level energy meters and connection of these energy meters to a central database.
- ✓ Connection of the existing energy meter of the renewables to the central database.
- ✓ At least two months of collected data for both types of energy meters.
- ✓ Fetching of weather forecast data for energy generation prediction.

Concerning the data that needs to be collected to build a training set for the energy prediction AI system, the initial cohort of products and machines that will be investigated will be limited to a small number of products, as well as the number of machines involved. The rationale behind this choice is rather simple, as it is not feasible, in two months of an equivalent production schedule, to collect data of all products in the catalogue. Moreover, not all products can be scheduled on every machine. Indeed, the study of the interchangeability of products and machines is an ongoing effort within the company, and the project is leveraged to gather even more insight into this aspect. Energy consumption data will be collected on four different machines, concerning the production process of four different products. These products, although mainly scheduled on a "preferred" machine, have been at least once scheduled and manufactured on a secondary machine. Moreover, it is a more feasible solution to focus the data collection and AI training on a limited number of combinations of products and machines, as this will deliver better performance, limited to these combinations than gathering data for a larger sample. The obtained results will indicate the applicability of the energy prediction system module, which will be further extended and applied to the whole catalogue in the final phase of the project.

The integration of the green APS in the current IT infrastructure requires a thorough understanding of the main modules of the system, and their interconnections with the existing ERP / MES systems. Broadly speaking, the green APS solution can be divided into the following:

- ✓ an AI energy consumption engine
- ✓ a job order allocation system
- ✓ a sequence optimization module
- ✓ a heuristic optimization engine

Moreover, the data requirements are the following:

- ✓ List of production resources
- ✓ Resource calendars
- ✓ Machine configuration parameters
- ✓ Change-over matrices
- ✓ Production rules
- ✓ List of production orders
- ✓ List of operations
- ✓ Bills of materials

The future workflow for the assessment of the production plan and schedule will be the following, with an emphasis on the interconnection of the modules above-mentioned and their specific data requirements.

As previously described, the person currently in charge of defining both the long- and short-term production plan will define a hypothetical / desired machine workload, assigning to each machine a given batch of product quantity, enough to satisfy i) the aggregated demand for a given product, ii) the minimum economic quantity, and iii) the batch size. Indeed, this step is still required, mostly unchanged from the as-is situation. However, important differences are to be highlighted: firstly, while the aggregation of different client orders is needed, as the heuristic optimization scheduling engine works in terms of production orders, the process of defining an extra quantity, exceeding the sum of requested product quantities, can be integrated into the APS solution. Indeed, giving this degree of freedom to the optimization engine will produce better results, as it can compare different scenarios, incorporating in the comparison energy consumption and costs data. Also, it is trivial to make the optimization engine aware of a minimum lot size. But the most important difference will be that the allocation of a given product to a selected machine by the hand-made desired schedule will be interpreted by the APS solution as an indication of the "preferred" machine. Nonetheless, the job order allocation module and the sequence optimization module will be informed, through the definition of the configuration parameters, change-over matrices, and various rules, of the possible alternative machines that can be employed for a given product. This information will be gathered from the ERP system. The definition of the machine that will be used for given production order will take into account the predicted energy consumption historical data, and inform the heuristic model of the predicted energy consumption. This information will be included in the cost function evaluation module, thus enabling the definition of an energy-aware schedule. It must be noted that this description focuses on the optimization procedure by taking into account only the shop-floor scheduling. Indeed, as previously described, all the products follow the same production cycle. Moreover, only the "manufacturing" step provides some degree of freedom for the APS to optimize the production plan. Indeed, only on the shop floor, there are alternative machines that can handle the same product.

Moreover, the APS system, connected to the MES IT system, will be able to constantly monitor the effective execution of the production schedule, in a real-time fashion. Indeed, the MES will be integrated with the job order allocation system and sequence optimization module, as the two components must be aware of the current shop-floor situation. The APS must be informed of the possible downtime of each machine, and the (predicted or planned) duration of a maintenance task. Such information will be much more precisely considered in the creation of the optimized list of production orders allocated to and sequenced in resources, concerning the current human procedure.

Nonetheless, the final output of the heuristic optimization engine will have to be approved to be effectively converted into a production plan and schedule. Indeed, not all operational and managerial aspects can be incorporated into the engine, and thus an approval process must be incorporated into the overall workflow.

C. Expected Outcomes

As already stated, the development of and integration of the new green APS is still an ongoing process. For this reason, we are not currently able to disclose achieved results. We proceed to describe the expected outcomes, and will later provide an update of the obtained results, and a discussion of the comparison with the desired KPIs.

Given the nature of the use-case manufacturing process, the expected influence of the energy consumption aspect in the definition of the manufacturing schedule, and the described limitations imposed by the change-over procedure, the following could be a very plausible most frequent output of the APS: given a lower energy fare rate during the night, all else being equal, and given the high average batch sizes, it would probably be ideal to schedule production during the night shifts, during which the requirements for the on-site operator will be lower, given that it is required to provide only surveillance and monitoring of the on-going manufacturing workload. Indeed, in this manner, during the day, when the higher-skilled workers are available, a long-lasting machine setup will be scheduled, to enable nightly production batches.

IV. CONCLUSIONS

The present work describes the design and case study of an advanced planning and scheduling system, whose research activities are carried out in the context of the “Green Advanced Planning & Scheduling” (GreenAPS) project funded under the EIT Manufacturing initiative - call 2022. The scope of the project is to integrate energy consumption optimization criteria into an existing APS solution, to enable more environmental-aware planning and scheduling, which would both benefit the environment as well as the economic impact for energy-constrained industries. We describe the current state and future desired state of Italian-based use cases, which would benefit from the application of such an innovative solution. The current state is analysed both from the current IT infrastructure as well as the current workflow for production planning and control, highlighting the constraints and limitations. While the project is still ongoing, and thus no definitive results have been recorded, we discuss the to-be result, as well as expected possible outcomes. Future outcomes will be discussed in more detail as the deployment of the green APS will be finalised and operational results will be available.

V. ACKNOWLEDGEMENT

This project has received funding from the EIT Manufacturing, Association (REF.: EIT Manufacturing 2022 KAVA 22181) - under grant agreement No 22181 (Green Advanced Planning & Scheduling).

REFERENCES

[1] APICS (2011). Operations management body of knowledge framework. APICS The Association for Operations Management. 3rd Edition.

[2] Beamon, B.M. (1999). Designing the green supply chain. *Logistics Information Management,* 12(4), pp. 332--342.

[3] De Burgos Jiménez, J., Lorente, J., (2001). Environmental performance as an operations objective. *International Journal of Operations & Production Management*, 21(12), pp. 1553--1572.

[4] Flynn, B.B., Schroeder, R.G., Flynn E.J. (1999). World class manufacturing: An investigation of Hayes and Wheel wright's foundation. *Journal of Operations Management*, 17(3), pp. 249—269.

[5] Hopp, W.J., Spearman, M.L. (2011). Factory Physics. 3rd Edition. Waveland Pr Inc.
[6] IPCC - Intergovernmental panel on climate change. Climate Change 2022. Mitigation of climate change. https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf
[7] Sarkis, J., Qinghua, Z., Kee-Hung, L., (2011). An organizational theoretic review of green supply chain management literature. *International Journal of Production Economics*, 130, p.p. 1--15.
[8] Slack, N., (2019). Operations Management. Pearson (9° edition).
[9] Srivastava, S.K., (2007). Green supply-chain management - A state-of-the-art literature review. *International Journal of Management Reviews*, 9(1).
[10] United Nations. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015 (https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E).
[11] Vieira, J., Deschamps, F., Valle, P.B., (2021). Advanced Planning and Scheduling (APS) Systems: A Systematic Literature Review. *28th ISTE International Conference on Transdisciplinary Engineering*, 16, pp. 385—394.
[12] Womack, J.P., Jones, D.T., Roos, D. (2007). The Machine That Changed the World. Free Pr; Reprint edition.
[13] World Economic Forum, (2022). Global Risks Report 2022. World Economic Forum, Geneva (Switzerland).