DIGITAL INDUSTRIES SOFTWARE

# Green scheduling

Using advanced planning and scheduling to minimize industrial $CO_2$ footprints


## Executive summary

This paper explores green scheduling and how implementing advanced planning and scheduling (APS) techniques significantly reduces carbon dioxide ($CO_2$) emissions for direct manufacturing operations across various industries. Additionally, we analyze a permutation flow shop (PFS) scheduling problem case to minimize total carbon emissions and optimize scheduling performance. We also show how an algorithm can contribute to reducing $CO_2$ footprints.

Ultimately, we introduce Opcenter™ APS software, the Siemens Digital Industries Software solution for manufacturing operation planning and scheduling, and illustrate how you can successfully adopt it to implement this algorithm and operationally reduce your manufacturing facility's $CO_2$ footprint. Opcenter is part of the Siemens Xcelerator business platform of software, hardware and services.

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# Introduction

In the current global landscape, sustainability is critical. The escalating effects of climate change have underscored the urgent need for businesses to adopt environmentally friendly practices.

In recent years, awareness of global warming and climate change has heightened, emphasizing the urgent need to mitigate carbon emissions across various sectors. Among these, the industrial sector stands out due to its substantial contribution to global energy consumption and carbon emissions. Consequently, manufacturing enterprises face increasing pressure to adopt sustainable practices and reduce their carbon footprint.

In response, organizations and governments have launched numerous initiatives to define and promote best practices for reducing emissions and meeting net-zero targets. This includes initiatives aimed at analyzing the $CO_2$ emissions of manufacturing industries and creating the necessary infrastructure and platform to make this possible. For example, the World Economic Forum initiative "Reducing the carbon footprint of the manufacturing industry through data sharing," to which Siemens is an active contributor.[1]

Another interesting initiative is the Carbon Footprint Catalog, which is a paper based on a survey conducted with 145 companies, belonging to 30 industry groups and 28 countries, by various authors and involving Columbia University and the Carbon Disclosure Project (CDP). The survey outcome is that the direct operations carbon footprint, without considering upstream and downstream emissions, can be up to 30 percent in some industries.[2]

Several authors propose APS solutions in manufacturing operations as an effective way of improving manufacturing efficiency, reducing energy consumption and limiting $CO_2$ emissions.

By integrating these solutions into their operations, manufacturing enterprises can enhance their operational efficiency and make significant strides towards sustainability.


## Shifting from greed to green

Previously, when reducing costs was the major concern for companies, the term greed scheduling was popular to indicate a planning and scheduling approach for minimizing costs. However, nowadays, green scheduling indicates a new approach to integrating sustainability considerations into production scheduling.

Sustainability is no longer an option but a necessity in today's global landscape. Businesses, particularly in the industrial sector, must take proactive steps to reduce their carbon emissions and adopt environmentally friendly practices. APS solutions can be instrumental in this endeavor, helping businesses reduce their $CO_2$ footprints and contribute to a sustainable future.

## Understanding green scheduling

Green scheduling represents a paradigm shift in traditional planning and scheduling methodologies, encapsulating the fusion of sustainability principles with operational imperatives. At its core, green scheduling embodies a holistic approach to resource optimization, pursuing efficiency and performance that harmonize with the need to reduce energy and $CO_2$ footprints. It is crucial to understand that energy consumption in manufacturing directly translates to $CO_2$ emissions.

Central to this concept is recognizing that environmental stewardship does not need to be at odds with economic viability. Rather, companies can integrate it seamlessly into existing operational frameworks to yield mutually reinforcing benefits. By optimizing resource allocation, production schedules and logistics through the lens of sustainability, organizations can achieve a perfect balance between cost-saving measures and environmental conservation. This entails a nuanced understanding of the interconnectedness between operational decisions and their environmental repercussions, where every scheduling choice becomes an opportunity to minimize energy consumption and reduce $CO_2$ emissions.

In practical terms, green scheduling entails reevaluating traditional metrics of operational efficiency to encompass environmental performance indicators. Rather than solely focusing on maximizing throughput or minimizing idle time, scheduling algorithms under the green scheduling paradigm prioritize energy-efficient production processes and emission reduction targets. This necessitates incorporating real-time data analytics and predictive modeling to anticipate energy-intensive tasks and optimize their scheduling accordingly. Moreover, green scheduling emphasizes the importance of synchronizing production schedules with renewable energy availability, leveraging periods of peak renewable generation to power manufacturing operations and mitigating reliance on carbon-intensive energy sources.

### Impacting $CO_2$ footprints with scheduling decisions

Optimizing production schedules directly influences energy use and, consequently, $CO_2$ footprints. Some key examples include:

- Optimizing production sequences: Arranging jobs to minimize machine switching and travel distances reduces the energy required for equipment operation
- Minimizing idle time: Reducing periods where machines are not actively working lowers overall energy demand
- Batching similar jobs: Grouping jobs requiring the same resources together optimizes energy use compared to frequent machine reconfiguration

By implementing these green scheduling practices, organizations can significantly reduce their environmental impact.

### Improving sustainability via supply chain collaboration

Green scheduling extends beyond the confines of individual production facilities to encompass the broader supply chain ecosystem. By optimizing transportation routes, inventory management practices and supplier relationships, organizations can minimize the carbon footprint associated with sourcing raw materials and distributing finished goods. This holistic approach requires collaboration across organizational boundaries, fostering partnerships with suppliers and logistics providers committed to sustainable practices. Using transparent communication and data-sharing mechanisms, stakeholders can collectively identify opportunities for reducing emissions throughout the supply chain, amplifying the impact of green scheduling initiatives.

For example, synchronized production schedules with supplier deliveries can minimize transportation distances and fuel consumption. Or optimizing inventory levels with collaborative forecasting and planning reduces unnecessary transportation and storage emissions. Collaborating with suppliers committed to sustainable practices creates a ripple

effect of green choices throughout the entire value chain. Leveraging this wider lens of green scheduling unlocks significant potential for reducing collective $CO_2$ emissions, fostering a sustainable future for manufacturing and beyond.

Central to the success of green scheduling initiatives is integrating APS software solutions equipped with dedicated features for environmental optimization. These software platforms leverage sophisticated algorithms and simulation capabilities to model various scheduling scenarios and identify the most environmentally sustainable course of action. By simulating the impact of various production schedules concerning energy consumption and $CO_2$ emissions, organizations can make informed decisions that strike an optimal balance between operational efficiency and environmental conservation. Moreover, these software solutions facilitate continual improvement with iterative optimization, enabling organizations to adapt their scheduling strategies in response to changing market dynamics and regulatory requirements. This includes:

- Collaborative planning, forecasting and replenishment (CPFR): Implement CPFR with suppliers to improve demand forecasting accuracy. This allows for more efficient production planning, reducing the need for excess inventory and transportation
- Multitier scheduling: Extend scheduling beyond internal operations to consider suppliers and distributors. By consolidating shipments and using backhauls, companies can significantly reduce transportation emissions
- Green procurement: Integrate environmental considerations into supplier selection. Partner with suppliers who prioritize energy efficiency and use sustainable materials
- Just-in-time (JIT) inventory management: Minimize raw material and finished product stockpiles. This reduces storage space requirements and lowers energy consumption for warehousing and refrigeration
- Sustainable packaging: Design and implement eco-friendly packaging solutions that use recycled materials and minimize waste
- End-of-life (EoL) product management: Integrate strategies for product take-back and recycling into the extended schedule. By designing products for disassembly and remanufacturing, companies can create a closed-loop system that minimizes waste and environmental impact

Overall, green scheduling represents a paradigm shift in the way organizations approach production planning and scheduling, transcending traditional metrics of efficiency to prioritize environmental sustainability.

By integrating sustainability principles into every aspect of the scheduling process, organizations can:

- Achieve a perfect balance between cost-saving measures and $CO_2$ footprint reduction
- Unlock new opportunities for operational excellence
- Contribute to the global effort to combat climate change


## Reducing $CO_2$ footprint challenges and the role of APS solutions

By leveraging predictive analytics and optimization algorithms, using APS solutions enables organizations to:

- Optimize production schedules
- Streamline inventory management
- Minimize transportation-related emissions

Leveraging accurate demand forecasting and real-time data analysis, APS systems empower businesses to align production levels with market demand, reducing overproduction and associated carbon emissions. Further, by integrating sustainability metrics into decision-making processes, APS software provides organizations with actionable insights to enhance resource efficiency and minimize environmental impacts across the supply chain.

## Optimizing production for sustainability with APS

One key aspect where APS solutions excel is facilitating the adoption of lean manufacturing principles, which prioritize waste reduction and operational efficiency. By identifying inefficiencies and bottlenecks within production processes, APS software enables organizations to streamline workflows, minimize energy consumption and reduce $CO_2$ emissions. Additionally, by optimizing production schedules to minimize downtime and idle capacity, APS solutions contribute to a more sustainable use of resources, thereby reducing carbon footprints associated with manufacturing operations.

APS software also plays a crucial role in enhancing supply chain visibility and resilience, which are paramount for reducing $CO_2$ footprints. By providing real-time insights into inventory levels, production capacities and transportation logistics, APS solutions enable organizations to make informed decisions that optimize resource use and minimize carbon emissions throughout the supply chain. Further, by facilitating collaboration and communication among stakeholders, APS software enhances supply chain agility, enabling organizations to respond rapidly to changing market conditions while minimizing environmental impacts.

Ultimately, these solutions leverage data analytics, optimization algorithms and real-time visibility to create more sustainable production schedules and supply chain operations. By considering environmental factors alongside traditional planning constraints, these solutions enable organizations to make informed decisions that minimize $CO_2$ emissions. Production scheduling plays a pivotal role in shaping the carbon footprint of manufacturing operations. By optimizing the sequence and timing of production tasks, scheduling algorithms can minimize energy consumption, idle time and transportation distances, reducing carbon emissions across the production process.

**Optimizing energy use and production with data-driven decisions**

Another significant benefit of using APS solutions lies in their ability to facilitate the adoption of renewable energy sources and sustainable manufacturing practices. By integrating renewable energy generation forecasts and energy consumption data into production scheduling algorithms, APS software supports organizations to optimize energy use and reduce reliance on fossil fuels. By enabling scenario analysis and what-if simulations, APS platforms empower organizations to evaluate the environmental impacts of various production strategies and identify opportunities for adopting cleaner technologies and processes.

Although there are many challenges for reducing $CO_2$ footprints within manufacturing and supply chain operations, APS software solutions offer a powerful means to overcome these obstacles and drive meaningful progress towards sustainability. By providing organizations with the tools and insights businesses need to optimize production processes, minimize waste and enhance supply chain visibility, APS solutions enable them to significantly reduce carbon emissions while simultaneously improving operational efficiency and competitiveness.
As the imperative for sustainable business practices continues to grow, the role of APS software in facilitating $CO_2$ footprint reduction will become increasingly indispensable in shaping a greener and more resilient future for organizations worldwide.

Adopting green scheduling practices using APS software solutions offers many benefits that extend far beyond environmental considerations. While reducing $CO_2$ footprints is undoubtedly a critical aspect, the advantages of green scheduling also encompass significant cost savings, operational efficiency improvements and enhanced brand reputation. Embracing sustainability in scheduling operations allows organizations to optimize resource use, minimize waste and reduce operational costs. By aligning production schedules with renewable energy availability and off-peak hours, businesses can capitalize on lower electricity rates, reducing energy expenses and enhancing profitability. Moreover, green scheduling enables organizations to streamline logistics and transportation operations, leading to reductions in fuel consumption and associated costs. Beyond financial gains, green scheduling fosters operational efficiency by optimizing production workflows, reducing idle capacity and minimizing downtime. By leveraging predictive analytics and optimization algorithms, APS software empowers organizations to make data-driven decisions that maximize productivity while minimizing environmental impacts.

Additionally, by enhancing supply chain visibility and resilience, green scheduling enables organizations to mitigate risks associated with disruptions and fluctuations in demand, improving overall operational performance. Further, prioritizing sustainability in scheduling operations enhances brand reputation and fosters customer loyalty. In an increasingly eco-conscious marketplace, consumers are actively seeking out businesses that demonstrate a commitment to environmental stewardship. By showcasing sustainable practices and initiatives, organizations can differentiate themselves from competitors, attract environmentally conscious consumers and build a positive brand image. By investing in green scheduling, companies demonstrate corporate social responsibility and align with the values of stakeholders, including investors, employees and communities. As public awareness of environmental issues continues to grow, organizations that embrace green scheduling not only contribute to a healthier planet but also position themselves for long-term success in a rapidly evolving business landscape.

**Using NEH multipass algorithms to reduce $CO_2$ footprints**

In recent years, the quest for sustainable manufacturing practices has led researchers to explore innovative approaches to reduce carbon emissions in manufacturing operations. One area of focus is optimizing production scheduling, specifically in PFS environments where the sequencing of operations plays a pivotal role. The flexible job ship scheduling problem is a variant of the optimal job scheduling problem. It is a type of scheduling optimization problem for allocating a set of jobs to a set of resources over a specific time horizon, which is harder than traditional job shop scheduling.

Traditional scheduling methods often prioritize efficiency and cost minimization, neglecting environmental considerations. However, emerging research highlights the potential of advanced scheduling algorithms to simultaneously optimize production schedules while minimizing carbon footprints.

Among these algorithms, the Nawaz, Enscore and Ham (NEH) algorithm has garnered attention for its effectiveness in addressing the PFS scheduling problem while considering environmental objectives.

The main characteristics of a NEH algorithm are that it performs heuristic scheduling with a multipass approach, meaning it considers different targets for optimization with each pass.

Heuristic scheduling involves using rules of thumb or algorithms to make scheduling decisions quickly, often without considering all possible options exhaustively. These methods prioritize efficiency over optimality, aiming to find satisfactory solutions for complex scheduling problems by leveraging simplified decision-making strategies based on experience or intuition.

NEH algorithmic scheduling begins with a set of jobs and their processing times on machines. It initially arranges jobs by decreasing total processing time. Then, it iteratively inserts each job into the sequence to minimize completion time. It employs a local search to enhance the sequence further, outputting an optimized schedule when it cannot make additional improvements.

The following steps summarize the scheduling execution process:

1. Arrange the jobs from an input sequence by their total processing times, ensuring a descending order.
2. The first two jobs in the arranged sequence are scheduled in a manner that minimizes the makespan.
3. Consequently, each subsequent job, which has not yet been sequenced, is inserted into the current sequence at a position that optimally reduces the makespan for the scheduled jobs. This insertion process is iterated until all jobs are sequenced.

Several studies[3,4] have underscored the efficacy of varying the NEH algorithm for improving scheduling performance with respect to carbon emissions reduction. By intelligently prioritizing manufacturing operations, an NEH-derived algorithm can minimize idle times, reduce energy consumption and optimize resource use, mitigating the environmental impact of production processes.

**A part manufacturing job shop application**

Consider a part manufacturing job shop that specializes in producing precision components for automotive engines. The shop operates multiple machining centers and must schedule a series of machining operations to fulfill customer orders while minimizing energy consumption and carbon emissions. The objective of this practical example is to minimize work-in-process (WIP), which is any inventory that has entered the manufacturing process that is no longer part of the inventory of raw materials but is not yet a finished product. In addition, the system places WIP in the asset category since the company has spent money on it. However, since the work is incomplete, the WIP has a lower value. Thus, reducing WIP is one of the most important steps in achieving lean manufacturing, leading to smoother workflow, greater liquidity, improved cash flow, better customer service, lower risks to the business and overall improved performance of a team's production.

Using a multipass algorithm, the shop's scheduling manager begins by inputting job specifications, including processing times, machine capabilities and environmental constraints.

Let's assume we have four identical jobs ($J_1$, $J_2$, $J_3$ and $J_4$), each with four operations. Table 1 shows the resources that can process each operation.

We need to allocate these operations to four machines ($M_1$, $M_2$, $M_3$ and $M_4$). All operations must be processed in order. For simplicity, we can assume there are no time constraints, so all jobs can start from the first time event. We can also assume that there are no lag time constraints and that machines are available 24/7. As an objective of the scheduling process, we set a goal to minimize WIP and $CO_2$ emissions.

## TABLE I

| Operation | Resource Group | Resources |
|---|---|---|
| $O_{1j}$ | $G_1$ | $\{M_1, M_2\}$ |
| $O_{2j}$ | $G_2$ | $\{M_2\}$ |
| $O_{3j}$ | $G_3$ | $\{M_3\}$ |
| $O_{4j}$ | $G_2$ | $\{M_2, M_4\}$ |

Figure 1 shows how the algorithm works. The scheduler determines a queue of jobs, considering the total $CO_2$ emissions for each job. If a job includes operations that can run on multiple machines, the scheduler will consider the combination producing the minimum $CO_2$ emission for each job.

Once it generates the queue, it selects the first job, fetches all its operations and assigns them to available resources. Then it recalculates the priority queue.

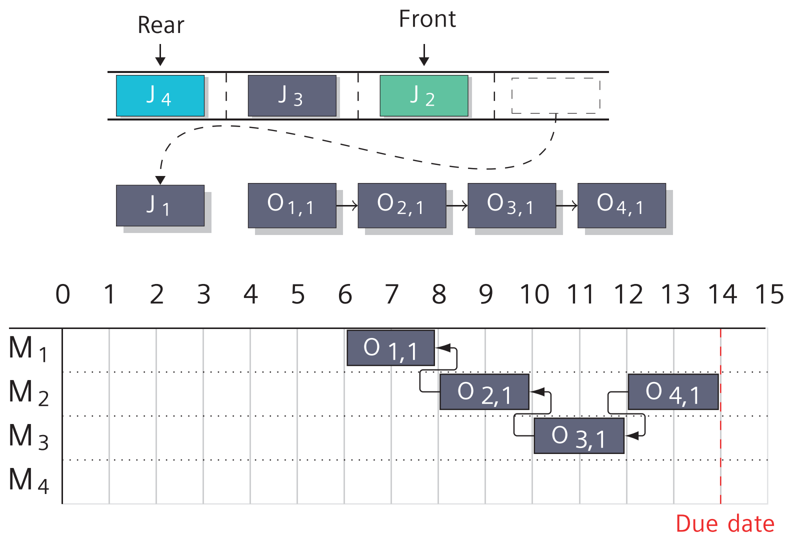


Figure 1.

Figure 2 shows how the algorithm proceeds subsequently to the first job. Once it schedules all operations of the first job, the scheduling algorithm selects the second job from the front of the priority queue ($J_2$), fetches all its operations ($O_{1,2}$, $O_{2,2}$, $O_{3,1}$ and $O_{4,1}$) and assigns them to available resources.

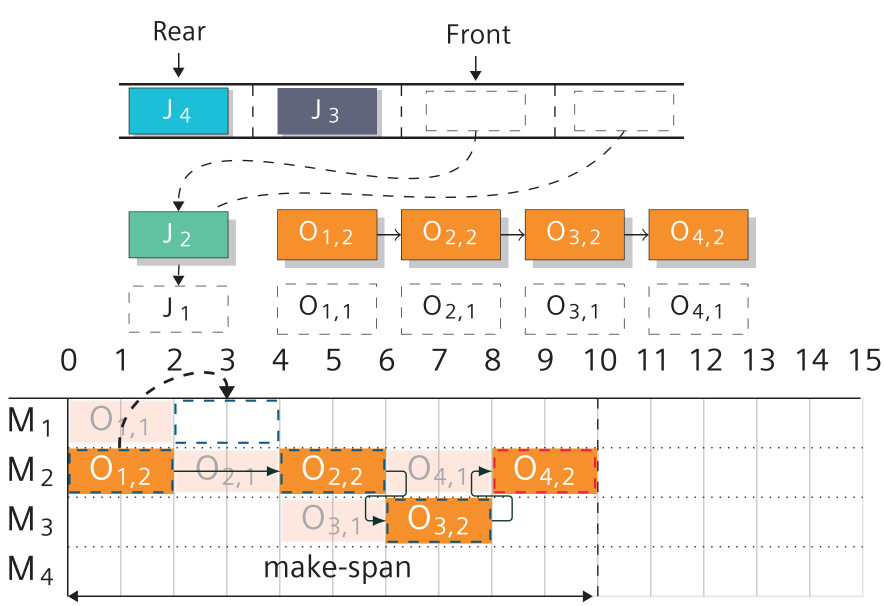


Figure 2.

Once it allocates the last operation, $O_{4,2}$, of $J_2$, to one of its resources, $M_2$, the algorithm reallocates the operations ($O_{1,2}$, $O_{2,2}$ and $O_{3,2}$) from the start time of operation $O_{4,2}$, which is shown in figure 3. As we can see, the minimize WIP forward algorithm does not reschedule operations $O_{2,2}$ and $O_{3,2}$ as there is no time gap between these operations and the last operation, $O_{4,2}$. However, the algorithm relocates the first operation, $O_{1,2}$, from resource $M_2$ to resource $M_1$. In addition, it delays the start time by two time units, so the new start time for the first operation will be at t = 2. The figure shows that this process minimizes the make-span for $J_2$ to the optimal value. By using this variation of the NEH algorithm, the job shop can minimize WIP while keeping an eye on $CO_2$ emissions, achieving a more sustainable production schedule, aligning with environmental objectives and meeting customer demands.

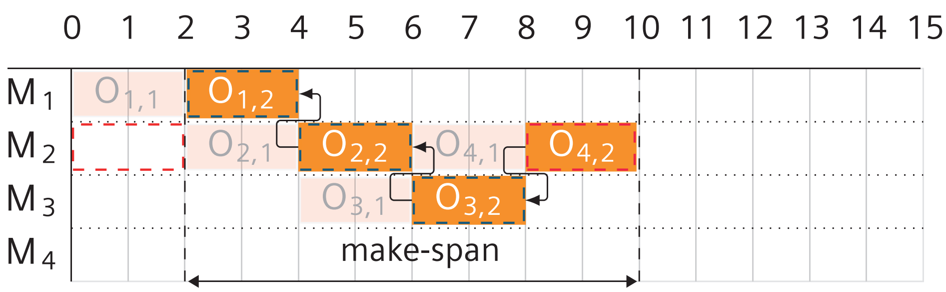


Figure 3.

**Leveraging Opcenter APS as a solution**
A Siemens solution for production scheduling is Opcenter APS.

Opcenter APS is a powerful and flexible tool for scheduling manufacturing operations using various types of scheduling approaches, including algorithmic, rule-based and event-based scheduling. With this solution, you can implement heuristic algorithms such as the proposed variation of the NEH algorithm. Additionally, in its scheduling model, it includes all the data required to evaluate energy and $CO_2$ footprints, along with costs, setup time and other constraints for operators, tools, the material available, etc.

By implementing an NEH algorithm using Opcenter APS, you can prioritize operations, considering not only the processing time but other parameters such as production cost per machine and operation, energy consumption, $CO_2$ emission, etc. Each of the parameters included in the scheduling model data can be combined using a special weighting rule that sums each parameter using a specific weight value. This weighting rule is helpful for fine-tuning your algorithm to find the perfect trade-off between various factors, therefore finding the balance between sustainability and profitability that is right for you.

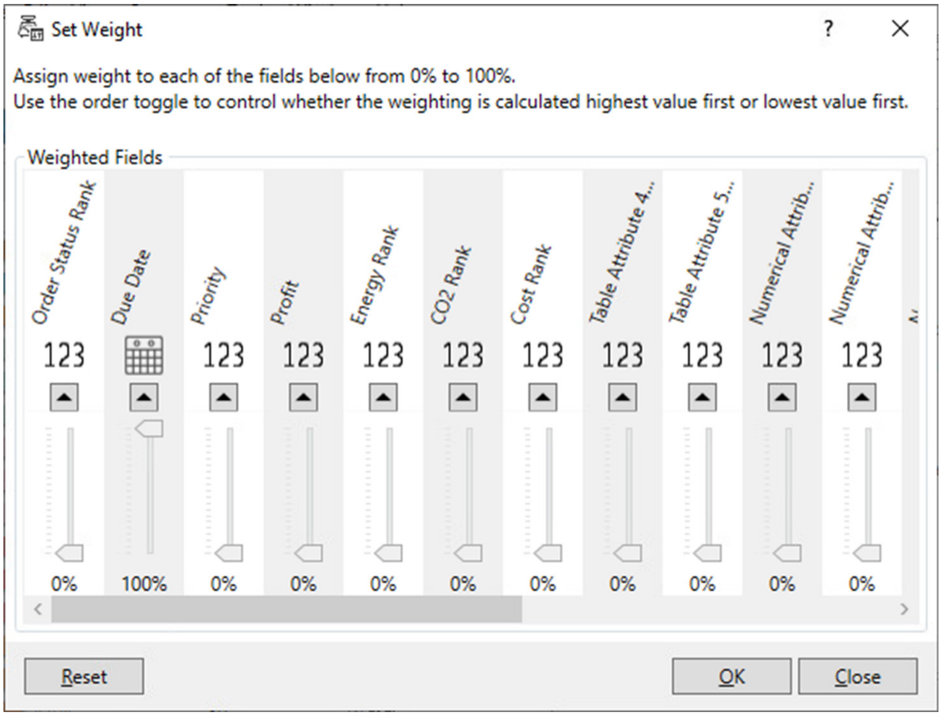


Figure 4.

# Conclusion

In an era where environmental consciousness is paramount, the imperative for manufacturing industries to reduce carbon emissions has never been clearer. As this paper highlights, the efficiency of manufacturing operations significantly impacts global $CO_2$ footprints, necessitating innovative solutions to minimize environmental impact while optimizing production processes.

The concept of green scheduling emerges as a transformative approach, seamlessly integrating sustainability considerations into production scheduling strategies and supply chain management. By prioritizing energy efficiency, resource optimization and emission reduction, green scheduling represents a paradigm shift towards a more sustainable manufacturing landscape.

Many authors proposed the heuristic approach, such as varying the NEH algorithm, as an effective way to perceive multiple objective targets, including $CO_2$ emissions, to find the right balance between sustainability and profitability.

With Opcenter APS capabilities, organizations can implement green scheduling practices effectively. Using optimization algorithms, a powerful set of configurable algorithms considering all relevant data and constraints from your facilities and scenario analysis tools, businesses can leverage Opcenter APS to minimize energy consumption, reduce carbon emissions and drive operational excellence.

Additionally, using Opcenter APS facilitates collaboration and stakeholder engagement, fostering a culture of sustainability across the supply chain. By providing actionable insights and facilitating data-driven decision-making, leveraging Opcenter APS enables organizations to achieve tangible results in their sustainability efforts.

In conclusion, Opcenter APS is not just a software solution; it is a catalyst for sustainable manufacturing transformation. By adopting Opcenter APS, organizations can lead the charge towards a greener future while simultaneously driving operational efficiency and competitiveness.

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