Project title

Public report

Project within Sustainable Production
Author Masood Fathi
Date 27-05-2025

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

The PREFER project (Digitalized and Optimized Production Planning for Energy-Efficient Production) addressed a significant challenge in modern manufacturing: how to digitally plan and optimize production processes while ensuring efficiency and energy awareness. In line with the objectives of the FFI Sustainable Production program, the project aimed to create practical tools and methods to promote resource efficiency, reduce environmental impact, and enhance industrial competitiveness through digitalization.

The project focused on two critical production domains: machining and human-robot collaborative assembly lines. For machining systems, we developed mathematical optimization models and algorithms for flexible transfer line balancing and sequencing. These models incorporated realistic industrial constraints such as task precedence, sequence-dependent setup times, fixture-tool compatibility, machine availability, and energy consumption in different operational modes such as active, idle, and standby. We used the epsilon-constraint method and a customized version of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to explore trade-offs between production cycle time and total energy consumption. These models were validated using real-case industrial data, and the results showed energy savings without compromising throughput. To address the challenge of scaling up for larger industrial problems, we designed a heuristic algorithm that combines rule-based task prioritization with a local search method. This approach produced near-optimal results in a fraction of the time required by exact solvers. It proved especially useful for large-scale scenarios where fast and reliable decisions are essential.

We developed models using mixed-integer linear and constraint programming for human-robot collaborative assembly lines. These models supported the dynamic assignment of tasks to either human workers or collaborative robots while considering robot energy states and task compatibility. We validated the models through a lab-scale testbed inspired by actual production setups. The results showed that task assignments could be optimized to balance energy efficiency with production cycle time.

A major outcome of the project was developing a decision support tool designed to make the developed optimization models and algorithms usable for production planners. The tool allows users to visualize and compare different planning configurations and scenarios, allowing experimentation with task assignment, sequencing, and equipment allocation. The tool's interface was built with usability in mind to meet the expectations and needs of industrial end-users.

We also explored a hybrid simulation-optimization approach. This framework connected a discrete-event simulation (DES) model with an intelligent optimization engine to assess production performance under uncertainty and variability. Using a real-world inspired case, we ran experiments that showed how the hybrid method could support better planning

decisions in dynamic environments. While the final version of the decision support tool was implemented without connection to DES, the knowledge gained from these experiments helped shape the tool's design and functionality.

The project also produced strong academic results. We published ten peer-reviewed papers, including six journal articles and four conference papers. These works addressed constraint programming in collaborative environments, heuristic methods for balancing machining lines, and a simulation-based optimization decision-support system. All the solutions developed in the project are tested using benchmark datasets and real-world case studies, ensuring their practicality.

On the educational side, the project hosted PhD and Master's theses. The project outcomes were also incorporated into courses at the University of Skövde, helping students access the latest production planning and optimization advances. The project further led to new collaborations with research groups in France, Germany, and the United States. These partnerships resulted in joint publications and opened opportunities for future research.

2. Sammanfattning på svenska

PREFER-projektet (Digitaliserad och Optimerad Produktionsplanering för Energieffektiv Produktion) tog sig an en central utmaning inom modern tillverkningsindustri: hur man digitalt kan planera och optimera produktionsprocesser med fokus på både effektivitet och energimedvetenhet. I linje med FFI-programmets mål för hållbar produktion syftade projektet till att utveckla praktiska verktyg och metoder för att främja resurseffektivitet, minska miljöpåverkan och stärka industrins konkurrenskraft genom digitalisering.

Projektet fokuserade på två kritiska produktionsområden: bearbetningslinjer och monteringslinjer med samverkan mellan människa och robot. För bearbetningssystem utvecklade vi matematiska optimeringsmodeller och algoritmer för balansering och sekvensering av flexibla transferlinjer. Dessa modeller tog hänsyn till realistiska industribetingelser som uppgiftsföljd, sekvensberoende omställningstider, fixtur- och verktygskompatibilitet, maskintillgänglighet samt energiförbrukning i olika driftlägen som aktiv, viloläge och standby. Vi använde epsilon-restriktionsmetoden och en anpassad version av den icke-dominerade sorteringsalgoritmen (NSGA-II) för att undersöka avvägningar mellan cykeltid och total energiförbrukning. Modellerna validerades med verkliga industridata och visade att energibesparingar kunde uppnås utan att produktionstakten försämrades.

För att kunna skala upp lösningarna till större industriproblem utvecklade vi en heuristisk algoritm som kombinerade regelbaserad prioritering av uppgifter med en lokal sökstrategi. Detta tillvägagångssätt levererade nära optimala resultat på betydligt kortare tid än exakta metoder och visade sig särskilt användbart i scenarier där snabba och tillförlitliga beslut krävs. Modellens flermålsfunktioner gav planeringsstöd för att balansera energieffektivitet med produktionsprestanda.

För monteringslinjer med människa-robot-samverkan utvecklade vi modeller med både heltalslinjär programmering och restriktionsprogrammering. Modellerna stödde dynamisk tilldelning av uppgifter till mänskliga operatörer eller samarbetande robotar, med hänsyn till robotens energitillstånd, ergonomiska risker och uppgiftskompatibilitet. Validering skedde genom laboratorieexperiment samt en fallstudie baserad på verklig produktionsmiljö. Resultaten visade att uppgiftstilldelning kunde optimeras för att balansera energianvändning, cykeltid och operatörers välbefinnande.

En av de viktigaste resultaten i projektet var utvecklingen av ett beslutsstödsverktyg som gör det möjligt för planerare att använda de utvecklade modellerna och algoritmerna i praktiken. Verktyget gör det möjligt att visualisera och jämföra olika planeringskonfigurationer, simulera resursallokering och undersöka energibesparande strategier. Gränssnittet har utformats för att vara användarvänligt och uppfylla industrins behov.

I ett tidigt skede testade vi även en hybridmodell som kombinerade diskret händelsesimulering med en intelligent optimeringsmotor. Med ett verklighetsinspirerat fall genomfördes experiment som visade att metoden kan stödja bättre planeringsbeslut i dynamiska miljöer. Även om det slutliga beslutsstödsverktyget inte byggdes på denna modell, påverkade erfarenheterna från dessa experiment verktygets utformning och funktionalitet.

Projektet genererade även starka akademiska resultat med tio fackgranskade publikationer, inklusive sex tidskriftsartiklar och fyra konferensbidrag. Dessa arbeten täckte ämnen som restriktionsprogrammering, heuristisk linjebalansering och simuleringsbaserade beslutsstödsramverk. Flera av dessa studier inkluderade benchmarkdata och metodinnovationer som stärker området hållbar produktionsplanering.

Utbildningsmässigt involverade projektet en doktorand och en masterstudent, och resultaten har integrerats i undervisningen vid Högskolan i Skövde. Projektet ledde också till nya samarbeten med forskargrupper i Frankrike, Tyskland och USA, vilket resulterade i gemensamma publikationer och nya forskningsmöjligheter.

Sammanfattningsvis har PREFER-projektet inte bara uppnått sina ursprungliga mål utan även bidragit med viktiga resultat för forskning, industri och utbildning. Projektet lägger en solid grund för framtidens hållbara, energieffektiva och digitalt integrerade produktionssystem i Sverige och internationellt.

3. Background

The PREFER project was initiated in response to growing demands in the manufacturing industry for smarter, more adaptable, and more sustainable production systems. Modern manufacturing environments are increasingly complex and dynamic, where humans, collaborative robots, and machines must work together efficiently. In these settings, production planning requires flexible and intelligent decision-making that can adapt to changing product mixes, energy constraints, and efficiency targets. Often static and isolated, traditional planning tools are no longer sufficient to meet these challenges, especially in high-mix, low-volume production contexts where variability and customization are high.

Recognizing this need, the PREFER project was funded under the FFI Sustainable Production program to develop a digital, optimization-based decision support tool that integrates line balancing, task assignment, and sequencing while explicitly considering energy consumption and throughput. These goals were aligned with the FFI program's objectives to foster resource-efficient, environmentally conscious, and globally competitive manufacturing. The project adopted a rigorous methodology, combining mathematical modeling, heuristic and metaheuristic algorithm development, and hybrid simulation-optimization experimentation to deliver both theoretical advances and practical tools for industrial application.

The research focused on two complementary production domains: machining and human-robot collaborative assembly lines. These domains were selected due to their industrial relevance and their potential for energy-aware optimization. In both cases, detailed mathematical models were formulated to capture operational constraints and objectives, and efficient solutions were developed to address computational challenges.

The project collaborated closely with industry partners for machining lines and used actual data from their facilities. In the first phase, a mixed-integer linear programming (MILP) model was developed to optimize task sequencing to minimize cycle time and energy. This model was validated against industrial benchmarks and demonstrated notable throughput and improvement in planning efficiency. In the second phase, the model was extended to incorporate machine tool assignment, adding complexity that required a new heuristic algorithm for scalability. This algorithm combined rule-based prioritization with local search techniques and was capable of solving large problem instances in a fraction of the time needed for exact approaches. A multi-objective optimization framework was also introduced and tested, allowing planners to evaluate trade-offs between productivity and energy efficiency.

In parallel, the project addressed energy-aware planning in human-robot collaborative assembly systems through both MILP and constraint programming models. These models accounted for robot energy states, task compatibility, and precedence relationships. The solutions supported the dynamic allocation of tasks between humans and robots in ways that minimized total energy usage without compromising cycle time or worker well-being. The models were evaluated in a lab-based testbed replicating industrial environments and further validated through comparative experiments using benchmark test problems.

Additionally, a hybrid simulation-optimization framework was explored during the project to evaluate how uncertainty and dynamic variability affect planning outcomes. This framework integrated discrete-event simulation with an intelligent optimization engine and was tested using a real-world inspired case.

A key outcome of the project was developing a digital decision-support tool based on validated optimization methods to support industrial adoption. The tool was designed to assist production planners in configuring, sequencing, and optimizing production plans, focusing on energy efficiency and operational performance. It includes features for visualizing alternative planning configurations, performing scenario analysis, and supporting energy-conscious decisions.

PREFER also delivered strong scientific output, resulting in ten peer-reviewed publications, six journal articles, and four conference papers covering most of the development made within the projects. Several of these works introduced benchmark datasets and novel modeling approaches that extended the project's academic and industrial impact beyond its immediate scope.

From an educational and capacity-building perspective, the project involved students at the master's and PhD levels, and its outcomes have been integrated into engineering courses at the University of Skövde. PREFER also established international research collaborations with institutions in Germany, France, and the United States, leading to joint publications and laying the groundwork for future initiatives.

PREFER was conceived to tackle critical challenges in sustainable and digitalized manufacturing. It has delivered on that promise by combining rigorous research with practical, validated tools. It supports the transition toward more intelligent, flexible, and energy-efficient production environments aligned with national and European industrial strategies.

4. Purpose, research questions and method

The PREFER project was initiated to tackle an important challenge in modern manufacturing: optimizing production planning in complex environments characterized by high product variability, fluctuating customer demands, and the joint operation of humans, robots, and machines. The primary purpose was to develop a digital decision support tool to help planners achieve sustainable, agile, and energy-efficient operations. This tool aimed to optimize both line balancing (LBO) and production sequencing (PSO) in machining and assembly lines, including those with human-robot collaboration (HRC).

This ambition was driven by a well-recognized gap between the vast academic literature on LBO and PSO and the industry's practical needs. Traditional models often fall short in capturing the complex and dynamic nature of real-world manufacturing, mainly when energy consumption, flexible resource allocation, and hybrid work configurations must be considered simultaneously. PREFER tried to bridge this gap by delivering advanced theoretical contributions and practically validated tools.

The project was guided by two core research questions:

RQ1: How can the load balancing and sequencing problem, particularly under human-robot collaboration, be effectively modeled and solved for machining and assembly lines?
The PREFER project adopted a structured research and development process grounded in real industrial challenges and informed by theoretical and practical considerations to address this research question. The goal was to develop optimization models and solution methods to support production planners in making energy-aware decisions for machining and human-robot collaborative (HRC) assembly lines.
We conducted a detailed analysis of production systems in close collaboration with our industrial partners. This analysis included mapping task dependencies, evaluating machines' and collaborative robots' physical and functional capabilities, studying energy consumption patterns across various operational states, and identifying resource constraints and layout limitations. These insights directly informed the design of our modeling frameworks and ensured that the developed solutions were relevant and applicable in real-world settings.
We developed a series of mixed-integer linear programming (MILP) models for machining lines to optimize task sequencing, machine assignment, and tool allocation while minimizing production cycle time. Real-world constraints such as sequence-dependent setup times, fixture and tool compatibility, and machine availability were incorporated into the models. To address the project's energy-efficiency goals, we extended these models to include machine energy consumption profiles across different operational states, active, idle, and standby, and developed a multi-objective formulation. This version enabled the simultaneous optimization of throughput and total energy cost. We solved the multi-objective model using the epsilon-constraint method and a customized version of the Non-dominated Sorting Genetic Algorithm II (NSGA-II). These solutions provided decision-makers with Pareto-optimal trade-offs, offering insight into how different planning configurations impact performance and energy usage. The models were tested and validated using real-case data provided by the industrial partners, demonstrating measurable reductions in cycle time and energy use.
To enhance scalability for large-scale industrial problems, we developed heuristic and metaheuristic algorithms that significantly reduced computational time while preserving solution quality. These methods were particularly effective in scenarios where the size and complexity of the problem rendered exact methods impractical. Our results showed that these algorithms could generate near-optimal solutions quickly, making them suitable for dynamic manufacturing environments where rapid planning adjustments are required.

We formulated MILP and constraint programming models for human-robot collaborative assembly lines to support flexible task allocation between human operators and collaborative robots. The models considered robot energy states (active, standby, and idle), human ergonomic constraints, task precedence relationships, and feasibility conditions based on task compatibility with humans or robots. These models enabled dynamic task assignments that could be adjusted based on system objectives, such as minimizing energy consumption or balancing workloads. We validated these models through lab-scale setups inspired by real industrial environments, allowing us to simulate collaborative task execution and energy-aware decision-making under controlled conditions.
The developed models and algorithms contributed directly to the goals outlined in the project proposal in both the machining and assembly line domains. They addressed the need for advanced planning tools capable of optimizing efficiency and sustainability metrics, aligning with the broader aims of the FFI Sustainable Production program. Ultimately, this work provided a solid foundation for the decision support tool developed later in the project, and the models serve as key components of a broader framework for digitalized intelligent production planning.

RQ2: How can an effective simulation-based optimization (SBO) approach be developed for integrated LBO-PSO-HRC planning to support real-time, energy-aware decisions?
To address this question, the PREFER project investigated the integration of simulation and optimization to enable effective production planning in complex environments. This effort is initiated from a key recognition that manufacturing systems are increasingly subject to uncertainty, variability, and competing objectives. Traditional static optimization methods, while powerful, are often limited in their ability to accommodate these real-world complexities. Therefore, we developed a simulation-based optimization (SBO) approach to evaluate and improve planning decisions under realistic operational conditions.
We developed a hybrid framework that combined discrete-event simulation (DES) with an intelligent optimization engine. The DES model was designed to capture the stochastic behavior of production systems, including task duration variability, equipment availability, and potential disruptions. On top of this simulation layer, the optimization engine explored planning configurations using a tailored algorithm to identify near-optimal solutions while considering multiple objectives. This hybrid SBO setup allowed us to dynamically evaluate and refine resource allocation decisions, providing a realistic and adaptive decision support mechanism.
The framework was applied to a real-world inspired case study, where we simulated a production line under various uncertain conditions. The results demonstrated that the hybrid SBO approach could successfully allocate resources to maintain throughput while adapting to system disturbances. These findings confirmed the relevance and potential of SBO as a tool for effective decision-making in complex manufacturing environments.

Although the final decision support tool implemented within the project did not include a direct DES component, primarily due to the preferences and practical needs of the industrial partners, the insights gained from the SBO experiments significantly influenced the tool's design. The hybrid experiments helped shape the underlying logic and structure of the planning framework for the developed tool.
In parallel, we developed tailored heuristic and metaheuristic algorithms to solve large-scale LBO-PSO-HRC problems efficiently. These algorithms enable fast computation under real-world constraints, where exact optimization methods are often too slow or infeasible. The heuristics ensure solution feasibility while maintaining high solution quality, making them suitable for time-sensitive industrial applications.
We incorporated multi-objective optimization methods into the solution process to support trade-off analysis between conflicting objectives, such as minimizing cycle time and reducing total energy consumption. By generating Pareto fronts, planners could explore different strategies and select the most appropriate solutions based on their specific operational goals and constraints.
The work under RQ2 resulted in a comprehensive and flexible methodology for integrated planning across machining and collaborative assembly lines. The simulation-based optimization framework, scalable heuristics, and multi-objective consideration provided a practical foundation for effective production planning towards more sustainable manufacturing.

5. Objective

The objectives of the PREFER project, as outlined in the original application, were clearly defined and remained unchanged throughout the project. The overarching goal was to develop a decision support tool for production planners to achieve digitalized, energy-efficient, and adaptive planning for assembly and machining lines. The focus was mainly on complex and dynamic production environments where humans, robots, and machines work independently or in collaboration.
The project aimed to close the gap between the theoretical advancements in line balancing and production sequencing optimization and their practical application in real-world manufacturing systems. This was motivated by the widespread observation that many companies still manage these tasks manually, which limits their ability to respond efficiently to changing production demands, increased product variation, and sustainability goals.
The project pursued four interrelated objectives to achieve this aim, all addressed within the project's life.

Objective 1: Analyze assembly and machining lines with industrial partners to identify relevant variables, constraints, and relationships influencing optimization objectives such as energy consumption and lead time.
To achieve this objective, the project involved an in-depth analysis of the production systems at the industrial partner sites and literature analysis, including both machining and assembly lines. The analysis focused on identifying critical variables, operational constraints, energy-related parameters, and system-specific requirements. The outcome of this phase was the development of general conceptual models for line balancing and production sequencing that apply to a wide range of industrial settings. This effort served as a foundation for the modeling work that followed.

Objective 2: Formulate mathematical optimization models, especially mixed-integer programming (MIP), capable of capturing system complexity in various line configurations, including fully automated (machining lines), manual, and HRC-enabled lines.
To fulfill this objective, mathematical optimization models were developed to formulate the line balancing and sequencing problems as MIP models. These models accounted for factors such as energy consumption, cycle time, equipment capabilities, human and robot skills, precedence relationships, and task accessibility. They were designed to be general enough to support both assembly and machining lines with different levels of automation, including lines with human-robot collaboration. For the machining line, the models were implemented and validated using real production data, and they were used to identify scenarios that reduce lead times and improve throughput without increasing energy consumption. For HRC, the test and validation have been done in a controlled environment in the lab.

Objective 3: Develop tailored heuristic algorithms that address problem complexity, multiple objectives, and practical real-world constraints.
To satisfy this objective and cope with the high computational complexity of real-life industrial problems, heuristic and metaheuristic algorithms were developed and tailored to the specific characteristics of the production environments studied. For problems addressed in this project with a high degree of combinatorial complexity, we designed a custom heuristic method based on rule-based task prioritization combined with local search. This approach enabled the generation of high-quality solutions within practical computation times, making it suitable for large-scale and time-constrained industrial applications.
In parallel, a metaheuristic optimization framework using a customized version of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was implemented to solve multi-objective formulations of the problem. This algorithm was adapted to handle complex constraints related to real-world problems provided by our industry partners, while

efficiently navigating the solution space to generate Pareto-optimal sets. These Pareto fronts revealed the trade-offs between key performance indicators such as throughput and total energy consumption, offering planners the flexibility to evaluate alternative configurations and select solutions aligned with operational priorities and sustainability goals.

Objective 4: Integrate the optimization methods with simulation to enable iterative improvement of production plans under uncertainty.

To fulfill this objective, the project developed and tested a hybrid framework that integrated the optimization models and heuristic algorithms with a discrete-event simulation (DES) environment. This integration allowed for the dynamic evaluation of production performance under realistic variability and operational uncertainty. The setup was designed to support scenario analysis, enabling users to test different production configurations and assess their impact.

The simulation-based optimization approach was successfully implemented and evaluated within the university setting using a real-world inspired case. These experiments provided valuable insights into how the optimization logic could respond to system disturbances and informed the structure of the decision support tool developed in the project. However, testing and integration with the industrial partner’s simulation models were not completed within the project timeframe, and this was a deliberate and mutual decision. The industrial partner already has a validated simulation model of their machining system and thus preferred to focus the project efforts on developing and verifying the optimization methods. It was agreed that the company’s internal simulation experts would handle the integration in the next phase, building on the methods and frameworks delivered by the project. This approach ensured that project resources were allocated efficiently and that the results remained aligned with both academic and industrial priorities.

Throughout the project, no significant deviations from the original objectives occurred. All initially planned goals were achieved and, in some cases, extended in scope. For example, the optimization framework developed for machining lines was expanded to include fixture assignment optimization besides tasks and tools assignment. Similarly, the models for human-robot collaborative assembly lines were extended to investigate the effect of assembly line layout on the solutions and production performance for the HRC assembly lines.

In conclusion, the PREFER project's objectives were met and enriched through practical implementation and feedback loops with the industry. The project has delivered scalable models, algorithms, and a prototype decision-support tool that helps manufacturers advance toward sustainable, efficient, and intelligent production planning.

6. Results and deliverables

The PREFER project has successfully met its objectives by developing advanced optimization models, algorithms, and a decision support tool to facilitate energy-efficient production planning and balancing in both machining and assembly lines. These outcomes align with the overall goals of the FFI program and specifically with the Sustainable Production sub-program, which emphasizes digitalization, resource efficiency, and sustainable manufacturing practices.

One of the project's primary focuses was integrating energy awareness into production planning. Several mathematical models and algorithms developed during the project included energy metrics as explicit optimization objectives. In machining systems, energy usage was modeled based on machine state profiles, while in collaborative assembly lines, robot energy consumption directly influenced task allocation and scheduling decisions. By incorporating energy as a key objective in optimization, the project assists production planners in analyzing and managing trade-offs between throughput and energy consumption, which is an important step toward aligning operational decisions with long-term sustainability and efficiency goals.

The project carried out two industrially grounded case studies to demonstrate the practical relevance of the optimization models and methods. One focused on a machining line, the other on a human-robot collaborative assembly line. In both cases, the developed tools evaluated how energy-optimized plans could reduce total energy consumption while maintaining or improving cycle time. This project validated the real-world applicability of the research and confirmed that improvements in production efficiency and sustainability could be achieved through careful planning and optimization. These findings support the ambitions of both the PREFER project and the FFI Sustainable Production program by advancing intelligent, energy-efficient manufacturing systems.

The project was delivered according to plan. All major deliverables were completed on time and with acceptable technical maturity. One notable success was the number of peer-reviewed scientific publications, which exceeded the expectations set out in the original proposal. These publications have contributed to the academic knowledge base in sustainable production planning and have established a strong foundation for further research and application.

Overall, the PREFER project has delivered on its original promises by producing validated optimization decision support tools and several optimization models and algorithms that are scientifically novel and practically relevant. The project outcomes have addressed the complexities of machining and assembly environments, incorporated real industrial constraints, and resulted in energy awareness and digital production planning advances.

These contributions align with the FFI program's core objectives and help pave the way for the continued development of sustainable production systems in Sweden.
The following sections present the project’s results and deliverables in detail.

Deliverable 1: Development of Optimization Models and Algorithms
To achieve the objectives of the PREFER project, we developed and validated several optimization models and algorithms to improve production planning through line balancing and sequencing. Our focus was primarily on two key manufacturing settings: machining lines and human-robot collaborative assembly lines. The following sections will present our developments and findings on machining systems and collaborative assembly lines.

Optimization of Machining Lines
One of the project's main goals was to develop optimization models for balancing and sequencing in machining lines. This was addressed by formulating a mixed-integer linear programming (MILP) model for Flexible Transfer Line Balancing Problems (FTLBP), tailored to the requirements of machining systems at the case company. The model integrated complex production constraints, including task precedence, station configurations, sequence-dependent setup times, fixture-tool compatibility, and machine availability, among other considerations.
A significant contribution in this part was the inclusion of multi-mode machine behavior, where each machining operation was associated with different energy profiles depending on the operational mode, such as processing, idle, or standby. This allowed the model to optimize not only for minimum cycle time but also for total energy cost. We applied the epsilon-constraint method to generate Pareto fronts illustrating trade-offs between productivity and sustainability objectives.
This model was validated using both benchmark datasets and real-case data from machining operations. The results demonstrated that optimized configurations could save energy without compromising production throughput. The developed framework supports production planners in identifying energy-optimal task allocations under realistic manufacturing conditions.
These developments are extensively presented in our paper: Nourmohammadi, A., Beldar, P., Fathi, M., & Mahmoodi, E. (2024). Balancing and scheduling of sustainable flexible transfer lines. IFAC-PapersOnLine. In that work, we developed a comprehensive MILP model to jointly address the balancing and sequencing of Flexible Transfer Lines in energy-aware machining environments. The model captures real industrial constraints and assumptions observed at the case study company. A key advancement in this study is the incorporation of detailed machine energy state modeling, which allows planners to assess energy costs under various production modes. We generated Pareto-optimal solutions and validated the model through extensive computational experiments. The results confirm that

the method can improve both throughput and energy efficiency. Figures 1, 2, and 3 display the Pareto fronts for problems of different sizes.

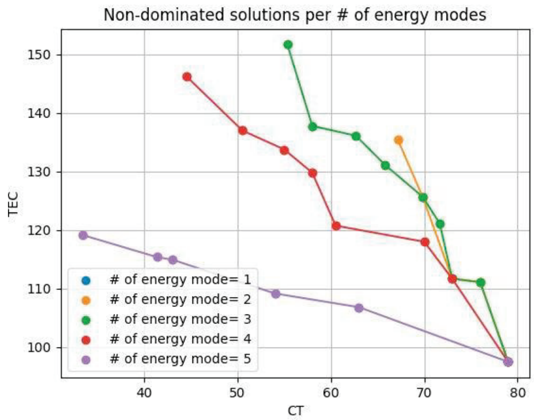


Figure 1. Pareto front for an 11-task machining line problem

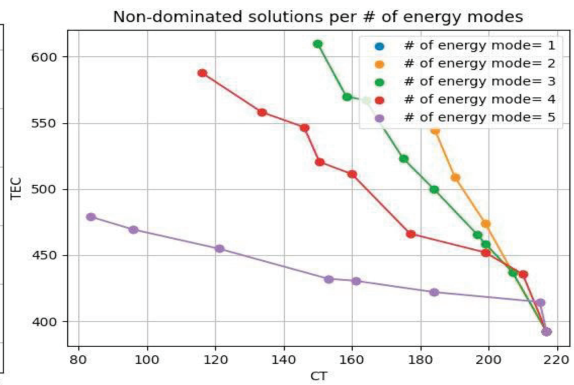


Figure 1. Pareto front for a 21-task machining line problem

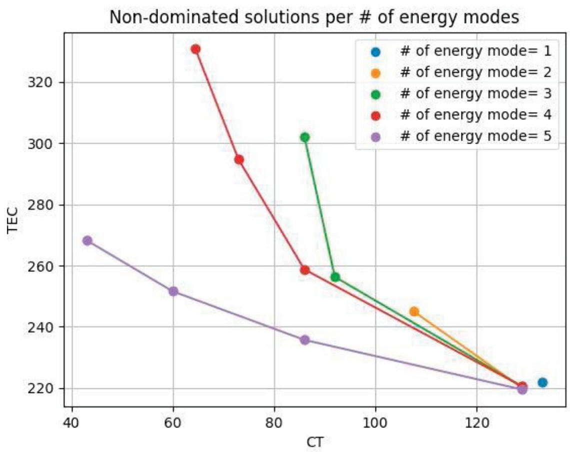


Figure 3. Pareto front for a 30-task machining line problem

In order to enhance the applicability of the framework to larger-scale problems, we also developed a heuristic method. More details of the heuristic can be found in our paper: Beldar, P., Nourmohammadi, A., Fathi, M., & Ng, A. H. C. (2024). A heuristic approach for flexible transfer line balancing problem. Procedia CIRP.

This heuristic uses a priority rule-based assignment combined with local search to produce high-quality solutions in a fraction of the time required by exact solvers. The algorithm effectively handles real-world constraints. We conducted comprehensive benchmarking that showed this approach offers near-optimal solutions with drastically reduced computational cost. This makes it particularly useful for dynamic industrial settings where rapid decision-making is critical.

Further extending the scalability of our optimization approach, we implemented a metaheuristic framework using a customized Non-dominated Sorting Genetic Algorithm II (NSGA-II), as reported in our study: Petersen, J., Nourmohammadi, A., Fathi, M., & Burmeister, C. (2024). Multi-objective optimization of transfer line balancing problem considering cycle time and energy expenditure. Procedia CIRP.

In this study, we focused on the multi-objective variant of the TLBP, minimizing both cycle time and energy expenditure. We adapted NSGA-II to preserve the structure of transfer lines while effectively navigating the solution space. Our algorithm was evaluated on 20 benchmark problems and a real-world case study from a project partner. The comparison with the epsilon-constraint method showed that NSGA-II offers superior diversity and convergence, producing a broader and more accurate Pareto front. Figures 4 to 7 present the key findings from this comparison.

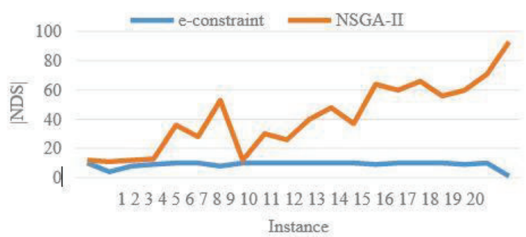


Figure 4. Comparison of the number of non-dominated solutions (|NDS|) between NSGA-II and epsilon-constraint

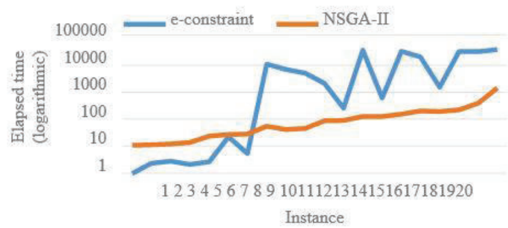


Figure 5. Comparison of elapsed time (in seconds) for both methods

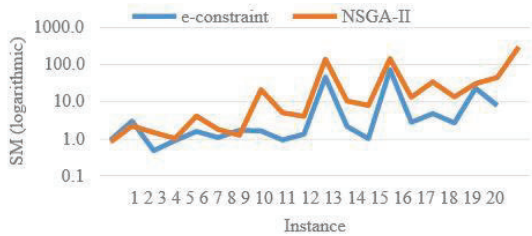


Figure 6. Comparison of the spacing metric (SM) indicating solution spread

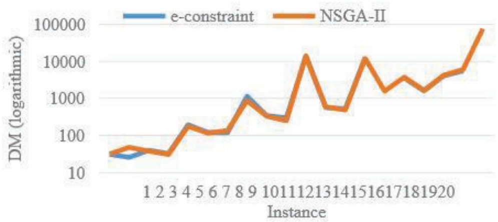


Figure 7. Comparison of diversity metric (DM) indicating Pareto front quality

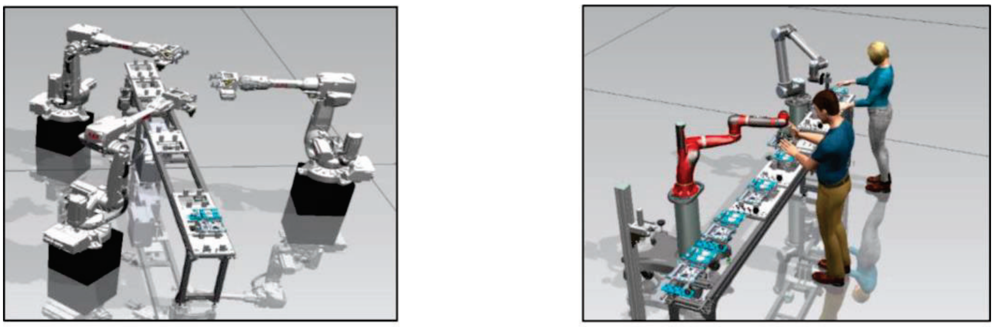
Through these developments, MILP modeling, heuristic search, and metaheuristic optimization, the project has successfully delivered a comprehensive, scalable, and energy-aware toolkit for balancing and sequencing in machining systems. These outcomes not only fulfill the planned deliverables but also directly align with the goals of the Sustainable Production sub-program, particularly in enhancing energy efficiency, digitalization, and sustainable production planning in industrial settings.

Optimization of Assembly Lines with Human–Robot Collaboration

In parallel with developing models for machining lines, we also addressed planning challenges in hybrid assembly environments where human operators or collaborative robots can perform tasks. We aimed to create dynamic, energy-efficient task allocations that enhance throughput while minimizing robot energy consumption. This work contributed directly to the planned deliverables for the PREFER project.

To fulfill this goal, we developed two complementary optimization models, one based on Constraint Programming (CP) and the other on Mixed-Integer Linear Programming (MILP). Both models integrated various real-world constraints, including task precedence, human or robot compatibility, layout-specific rules, and detailed energy profiles for robotic operations. Robots were modeled across distinct energy states such as active, standby, and idle, and energy consumption was explicitly considered in both task sequencing and resource assignment. We also introduced a dynamic task allocation mechanism in which operations could shift between humans and robots based on feasibility and planning objectives.

An illustration of the collaborative assembly layout we used in our validation environment is shown in Figure 8.



(a) (b)

Figure 8. An illustration of an assembly line with (a) industrial robots and (b) collaborative robots

To support rapid and flexible planning in energy-aware collaborative environments, we developed a CP-based optimization model for the Human–Robot Collaborative Assembly Line Balancing Problem (HRCALBP). The model was designed to minimize cycle time and robot energy consumption while satisfying constraints related to task precedence and agent compatibility. A central feature of the model is its explicit modeling of energy consumption across robot states, making it possible to generate solutions that balance production performance with sustainability.

We validated this model extensively using a lab-scale collaborative assembly setup inspired by a real industrial scenario. More than 1000 problem instances were generated with varying sizes and complexities to evaluate the CP model's scalability and performance. We also compared its results against those of a MILP-based formulation. The CP model delivered high-quality solutions across all test categories and consistently outperformed MILP in terms of computational time. This comparison is summarized in Figure 9, which presents a percentile-based evaluation of objective performance across problem categories.

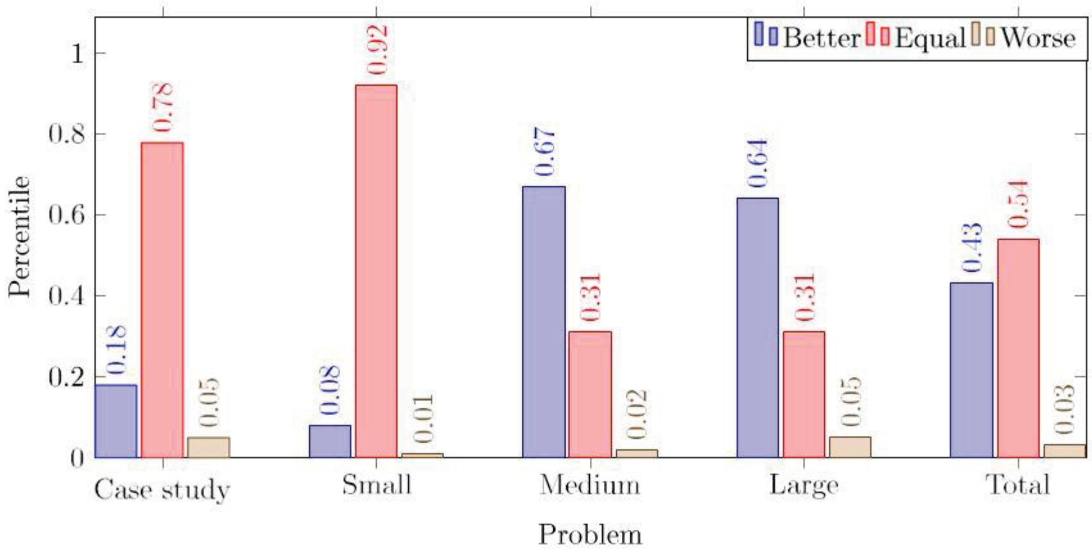
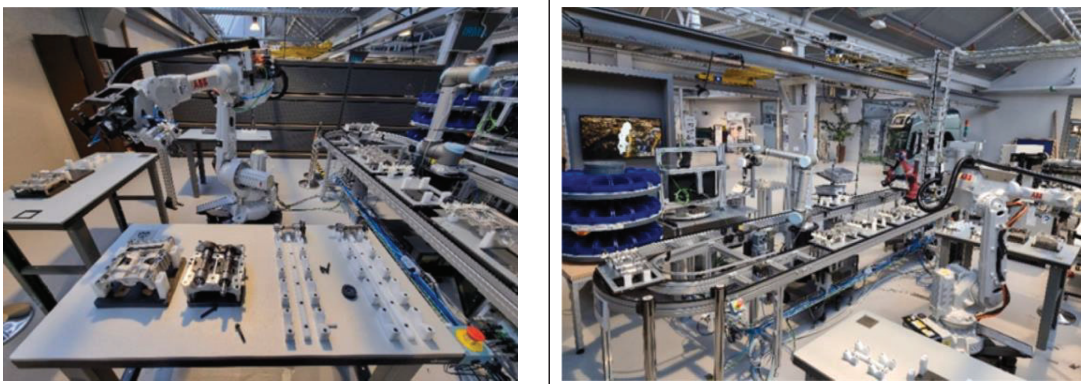


Figure 9. Comparison of CP and MILP over the percentile of objective status per problem category

These results demonstrate that the CP approach is a powerful and practical tool for energy-aware planning in collaborative assembly and supports rapid re-planning when needed in industrial settings. Details of this work can be found in our published study: Nourmohammadi, A., Arbaoui, T., Fathi, M., and Dolgui, A. (2025). Balancing human-robot collaborative assembly lines: a constraint programming approach, Computers & Industrial Engineering.

In complementary work, we developed an MILP-based optimization model focused on the joint balancing and scheduling of human-robot collaborative assembly lines. This model assigns tasks to humans or collaborative robots based on compatibility and explicitly includes energy consumption as a secondary objective. Each task has a specific energy cost if performed by a robot, and the optimization minimizes total energy use and production cycle time.

We validated the MILP model using a real-world collaborative assembly case study. Figure 10 shows the study layout and partially assembled product, highlighting the collaborative configuration used for evaluation.



(a) A semi-assembled MBS and its components | (b) AL-HRC layout

Figure 10. The case study: (a) a semi-assembled MBS and (b) the AL-HRC layout

Results from this study demonstrated that our MILP model can generate energy-efficient task allocations without compromising cycle time. In particular, task assignment decisions were found to impact both energy usage and overall throughput. The model helps identify optimal configurations that simultaneously achieve production and sustainability objectives by evaluating alternative assignments.

This MILP-based framework provides a robust and scalable decision support tool for production planners working with hybrid human-robot systems. It is critical in enabling early-stage, energy-aware planning in digitally integrated production environments. The complete formulation and results are presented in our study: Nourmohammadi, A., Fathi, M., and Ng, A. H. C. (2024). Balancing and scheduling human-robot collaborated assembly lines with layout and objective consideration, Computers & Industrial Engineering.

The CP and MILP models we developed offer a complete framework for energy-aware optimization of collaborative assembly lines. These contributions satisfy the project's objectives and directly support the goals of the FFI Sustainable Production sub-program.

Deliverable 2: Development of a Decision Support Tool

As the project's final product, and to enable the applied use of the optimization models and algorithms developed within the project, a decision support tool has been developed for easy validation and comparison of alternative planning configurations. This tool allows planners to optimally schedule production and assess different scenarios and trade-offs under realistic constraints. The tool reflects the digital transformation goal of the project by providing decision-makers with the ability to conduct advanced planning through an intuitive interface. Following the planned deliveries in the project, development was done, and experiments were conducted, as explained below.

Hybrid Simulation-Optimization Framework

During the project, we designed and tested a hybrid simulation–optimization framework for adaptive resource allocation in production lines. This framework closely aligns with PREFER's goals, particularly developing a decision support system for efficient production planning. It combines a discrete-event simulation environment with an optimization engine that uses a customized intelligent algorithm to identify near-optimal solutions. This integration is particularly useful for dynamically adjusting to varying resource availability and handling real-world uncertainties and system disturbances.

The main contribution of this hybrid framework is its capacity to model complex and stochastic production environments. The simulation component accounts for random task durations, machine availability, and variability in execution times. The optimization engine works in tandem to evaluate different planning configurations based on multiple objectives, including throughput, resource utilization, and responsiveness.

We conducted a series of experiments based on real-world inspired cases to evaluate the system's capabilities and performance. Results showed that this hybrid simulation–optimization method could improve production planning outcomes under uncertainty by offering high-quality solutions that are adaptive and realistic. The framework empowers planners to conduct experiments and test alternative strategies before implementation, which helps reduce planning lead time and improve operational robustness.

This development supports PREFER's ambition to advance digitalized production planning. By connecting a customized optimization algorithm to a dynamic simulation model, we created a hybrid system that is a practical step toward sustainable production. Figure 11 depicts the overall system architecture of this hybrid framework.

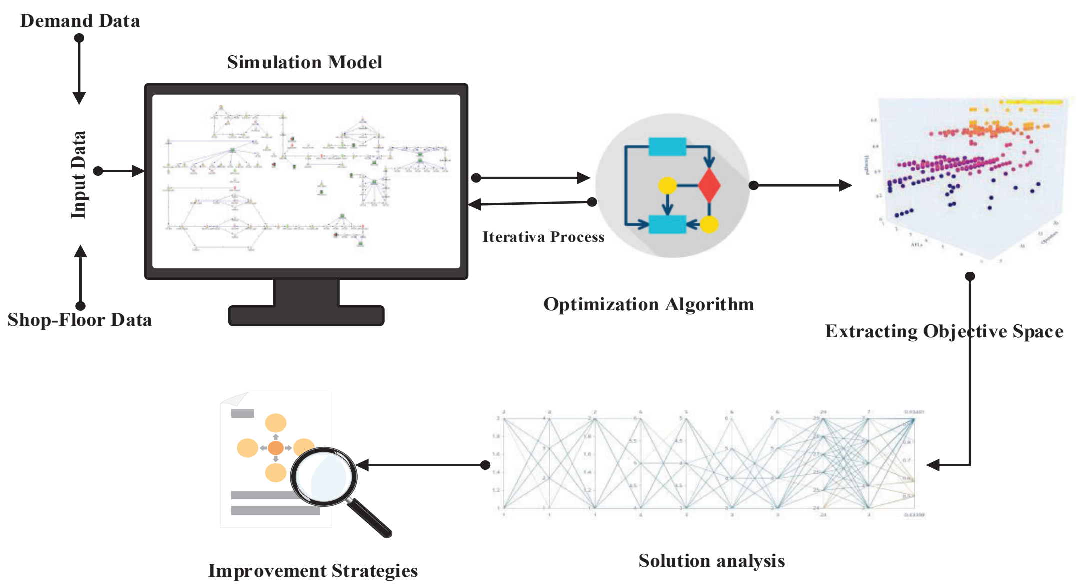


Figure 11. System architecture of the integrated simulation and optimization environment

More details on this development, including the experiments that were conducted and evaluated, can be found in our published study: Mahmoodi, E., Fathi, M., Tavana, M., Ghobakhloo, M., & Ng, A. H. C. (2024). Data-driven simulation-based decision support system for resource allocation in Industry 4.0 and smart manufacturing, Journal of Manufacturing Systems.

This study demonstrates the early testing and validation of the hybrid simulation–optimization concept. However, due to the nature of the problem, time constraints, and the interest of our industry partners, the final version of the decision support system was developed without discrete-event simulation. Instead, the tool retained its ability to perform configuration testing and scenario analysis directly through the optimization layer. This approach allows users to test alternative planning strategies and quickly obtain high-quality solutions, thereby maintaining the core goals of flexibility, efficiency, and applicability in real industrial contexts.

The Decision Support Tool

As part of the project's commitment to enabling advanced, digitalized, and energy-efficient production planning, an optimization-based decision support tool has been developed. This tool serves as a practical implementation of the optimization methods and mathematical models devised within the project and contributes directly to the planned deliverable, which aims to optimize production systems through integrated planning of tasks, machines, and resources.

The tool is designed with a user-friendly interface and a structured input/output process. It accepts the input data via an Excel file, which defines the problem parameters such as tasks, machine capabilities, setup and processing times, tool compatibility, and fixture constraints in an extended version. Based on this input, the tool internally invokes an optimization algorithm developed during the project, tailored to the problem, to generate high-quality solutions in very short computational times. The output includes a visual Gantt chart showing the scheduled sequence of tasks across machines and resources, and a detailed solution file exported in Excel format, summarizing task-to-machine assignments, tool selections, and cycle time performance.

The developed decision support tool is versatile and modular. It supports three levels of optimization complexity, addressing different layers of industrial needs:

Level 1: Task-to-Machine Assignment Optimization: At the most basic level, the tool determines optimal task assignments to machines/resources, respecting all precedence and compatibility constraints.

Level 2: Joint Task and Tool Assignment Optimization: The second level extends the decision-making capability by integrating tool selection into the optimization process. The model ensures that tool constraints, changeovers, and compatibility conditions are satisfied while minimizing cycle time and improving resource utilization.

Level 3: Simultaneous Task, Tool, and Fixture Assignment Optimization: As an advanced extension beyond the original scope of the project, the tool has been further developed to handle a more complex variant of the problem that includes fixture assignment along with task and tool planning. This fully integrated approach provides a holistic view of production scheduling.

The tool has been extensively validated. It has been benchmarked against results from the scientific literature and shown to produce high-quality solutions that are near-optimal. Moreover, industry validation has been performed for the first two levels of the tool using real-world data provided by the project's industrial partners. These validation exercises confirmed the tool's effectiveness in significantly reducing planning lead time and enhancing decision-making quality. Due to time limitations in the final project phase, industrial validation for the third level was not feasible. However, computational experiments have demonstrated that even this advanced model performs effectively and compares favorably to existing scientific approaches.

The following section visually represents the tool's workflow and user interface, illustrating the three-step process: input data handling, optimization execution, and solution visualization. This tool represents a concrete, deployable project outcome and positions the developed optimization research for real-world adoption in industrial settings.

Tool Interface Explanation and Workflow

The optimization tool follows a structured, step-by-step flow, from input selection to data visualization, optimization, and results interpretation. Each screenshot below (Figures 12 to 16) represents a major functional component of the tool.

Figure 12 provides an overview of the tool interface. It introduces the user to the context of the planning task and reflects the type of production environment the tool is designed for. The displayed layout of a production line with multiple machining stations. This screen sets the industrial context for what follows in the optimization pipeline.

Figure 12. The decision support tool interface

As seen in Figure 13, the user selects the optimization problem that needs to be solved. There are three options: (1) assigning tasks to machines without tool and fixture consideration, (2) assigning tasks with tool selection, and (3) assigning tasks along with both tool and fixture selection. This tri-level structure supports modular and scalable use of the tool, allowing planners to address increasingly complex problems depending on the production scenario. As can be seen, the input data can also be easily provided from a data source.

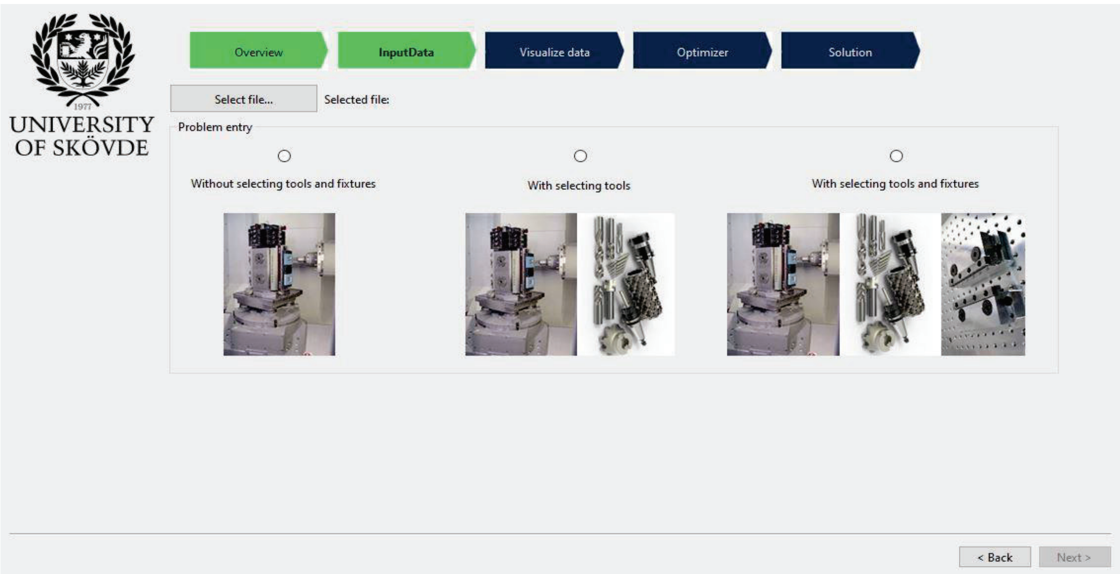


Figure 13. Optimization Problem Selection and Input Data Configuration

Each selection is visually represented with relevant images. Once the optimization problem is selected, the user uploads an Excel-based input file containing detailed task, machine, tool, and fixture data as applicable. Then, the precedence relationship of tasks is automatically identified and visually represented for any revisions if needed. Figure 14 provides a graphical representation of the task precedence structure and technological relationships. It visualizes how tasks are interdependent and highlights branching and merging paths in the task flow. This visualization helps users verify the correctness of the task network and assess any needed modifications in the input data.

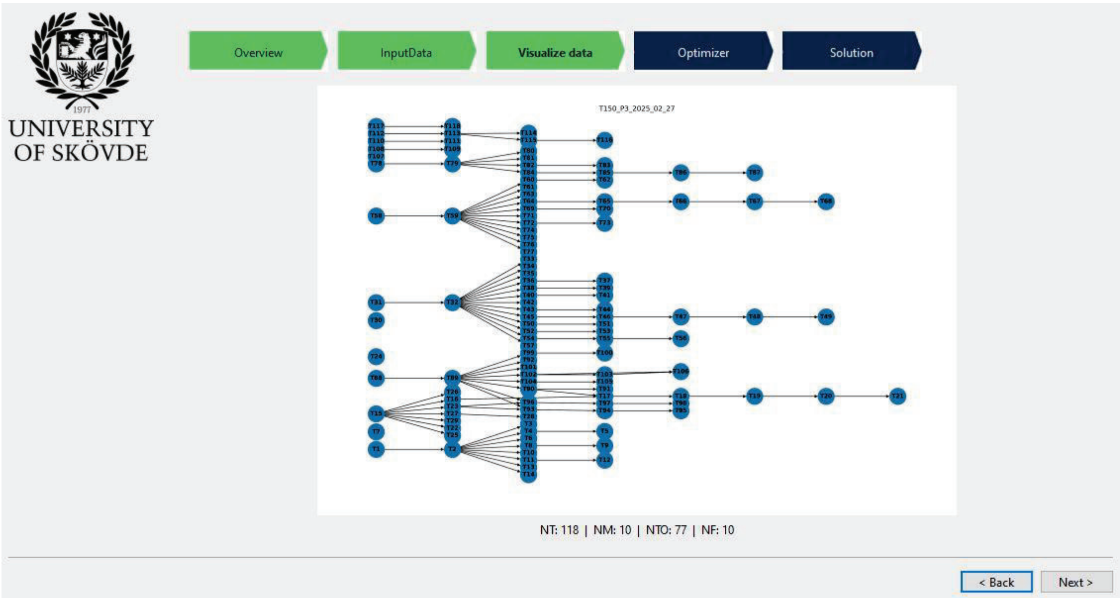


Figure 14. Task Precedence and Visualization Graph

Once data has been loaded and validated, the user activates the optimization engine via the "Start Optimizer" button. The optimization model solves the task assignment problem according to the selected optimization problem, considering constraints such as machine-tool-task compatibility, precedence, setup requirements, and load balancing.

As shown in Figure 15, the results represent the individual cycle times on each machine and the overall line cycle time. At the bottom, the total time to compute the solution is also displayed, often less than a few seconds, demonstrating the tool's computational efficiency and suitability for near real-time planning.

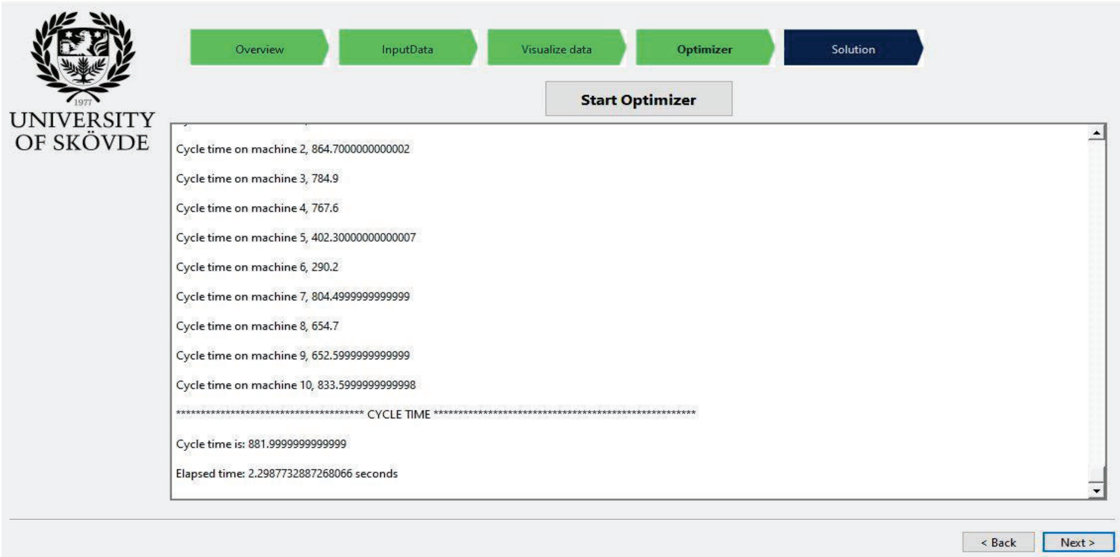


Figure 15. Optimization Process Screen

Figure 16 shows the solution visualization interface. A color-coded Gantt chart displays how tasks are assigned to machines/resources over time, enabling the user to visually assess the load distribution and utilization across machines/resources. Each row represents a machine, and each block shows an assigned task labeled by ID. The chart allows users to identify idle periods, bottlenecks, and the overall sequence of operations. The tool also displays the total optimized cycle time in seconds at the bottom of the chart.
This output can be exported to Excel, enabling further analysis, archiving, or direct use in production scheduling documents.

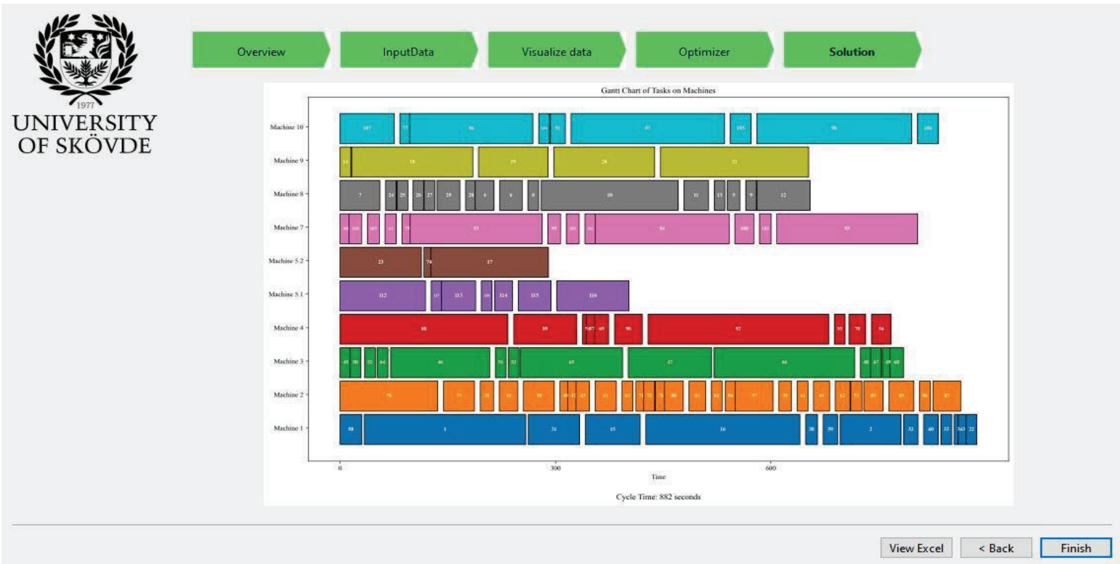


Figure 16. Gantt Chart of Task Assignments

The developed optimization tool supports an intuitive, structured workflow tailored for industrial use. From configuration through computation to visualization, the tool reflects the PREFER project's objective to develop a deployable, reliable decision support tool capable of handling complex production planning challenges.

Deliverable 3: Scientific Publications and Dissemination

The project has generated ten peer-reviewed publications (six journal articles and four conference papers), which exceed the original dissemination goals outlined in the proposal. These scientific contributions span the full scope of the project, including line balancing and sequencing in flexible and sustainable production systems, energy-aware optimization, collaborative automation involving humans and robots, and the development of a hybrid simulation-optimization decision support system. The depth and diversity of these publications ensure the project's long-term academic and industrial impact. They have been published in reputable journals such as Computers & Industrial Engineering and the Journal of Manufacturing Systems, as well as well-regarded conference proceedings, including IFAC-PapersOnLine and Procedia CIRP. These publications communicate the project's methodological and applied contributions and form a strong foundation for future research initiatives and collaborative opportunities.

Beyond scientific publications, the project has conducted a variety of outreach and dissemination activities to ensure strong industrial relevance and societal engagement. A yearly public workshop was organized, inviting academic and industry participants. The project team presented key results and ongoing developments during these events and collected valuable feedback. In connection with the public workshops, private individual workshops were held with the industrial partners to discuss technical details and define the next steps. These structured activities were complemented by many additional informal working meetings between the project team at the University of Skövde and the partner companies. These interactions supported close collaboration and ensured the practical implementation of project results.

The knowledge generated during the project was also systematically transferred to students and early-career researchers through thesis supervision. One Master's thesis was completed, and one PhD thesis was initiated and progressed on topics directly related to the project's focus. These student efforts contributed meaningfully to developing and validating key models and tools while providing students with hands-on experience working with industrial challenges and real-world data.

Furthermore, project findings have been integrated into educational content at the University of Skövde, particularly within production systems and optimization courses. The close collaboration with industry and the resulting models and planning approaches have been introduced to students through lectures and project-based learning activities, strengthening the link between research, education, and industrial practice.

In summary, the project dissemination ensured broad and meaningful knowledge transfer through academic publications, stakeholder workshops, thesis projects, integration into university education, and close collaboration with industrial partners. These dissemination efforts contribute directly to the objectives of the FFI program by enhancing industrial competitiveness, supporting sustainable production practices, and promoting digital transformation within Swedish manufacturing.

Contribution to the Objectives of the FFI Programme and the Sustainable Production Sub-Programme

The PREFER project has contributed significantly to the overarching goals of the FFI program by developing and validating a comprehensive, digitalized, and energy-conscious production planning framework, which directly addresses the program's ambition to strengthen Sweden's industrial competitiveness through innovation in sustainable manufacturing. The project outcomes are also strongly aligned with the objectives of the specific sub-program on Sustainable Production, which calls for research that advances resource efficiency, productivity, digitalization, and industrial relevance.

From a general perspective, the FFI program emphasizes the development of advanced, knowledge-driven technologies and methods that enhance Sweden's industrial ecosystem and technological independence. PREFER aligns with these priorities by generating novel research outcomes through optimization models, decision support tools, and simulation frameworks that are academically rigorous and industrially validated. Through close collaboration with industrial partners such as Volvo and Daloc, the project has ensured that the developed methods are anchored in real operational challenges and can deliver measurable improvements in planning lead time, energy use, and throughput. These contributions support the FFI program's vision of knowledge-based innovation, technology transfer, and long-term competence development in critical manufacturing domains.

Concerning the Sustainable Production sub-program, PREFER responds directly to several defined focus areas. First, the project tackles resource efficiency by developing energy-aware optimization models for machining and assembly lines. By incorporating machine energy modes and robot consumption profiles into the planning, the project enables decision-makers to evaluate trade-offs between cycle time and energy cost, promoting more sustainable operations. This is particularly evident in the MILP-based models and intelligent algorithms developed for flexible transfer lines and human-robot collaborative assembly, where energy consumption is treated as an optimization objective. The developed solutions allow companies to reduce unnecessary energy usage, better utilize equipment, and contribute to environmental sustainability without compromising productivity.

The project also advances the sub-program's goal of digitalizing production planning and decision support. The simulation-based and optimization-driven planning environment developed within the project is shown to be practical. The machining line optimization tool, for example, accepts structured Excel input, performs complex optimization across task, tool, and fixture layers, and provides results in the form of Gantt charts and Excel-based outputs. This digital workflow supports transparent, reproducible, and flexible planning, aligned with Industry 4.0 principles. The tool's usability, speed, and solution quality make it suitable for practical deployment in industrial settings, thus bridging the gap between academic research and operational application.

The project also supports the program's emphasis on collaboration between academia and industry. Close cooperation with Volvo and Daloc throughout the project lifecycle ensured continuous feedback, real-world validation, and mutual knowledge exchange. These partnerships enhanced the technical quality of the deliverables and promoted industrial relevance and uptake. The project team at the University also engaged in scientific dissemination, publishing ten peer-reviewed papers in reputable journals and conferences, thereby contributing to the academic excellence dimension of the FFI program.

In terms of long-term competence development, PREFER has provided a strong platform for further research, student engagement, and curriculum enrichment. The developed models and tools have been integrated into thesis projects and are expected to be embedded into course content and advanced training modules at the University of Skövde. This ensures that the project's outcomes will continue influencing education and skills development in digital production planning beyond the project's timeline.

In conclusion, the PREFER project delivers on the FFI program's overarching objectives by combining scientific novelty, industrial applicability, and sustainability-oriented innovation. It contributes directly to the Sustainable Production sub-program by enhancing digital decision support, promoting energy-efficient operations, and enabling flexible production systems. Through its structured, validated, and transferable results, the project strengthens the foundation for smarter, greener, and more competitive manufacturing in Sweden.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	See below
Be passed on to other advanced technological development projects	X	See below
Be passed on to product development projects		
Introduced on the market		

Used in investigations / regulatory / licensing / political decisions		

Increase knowledge in the field.
The PREFER project has produced substantial scientific contributions, including ten peer-reviewed publications in respected journals and conferences. These publications address modeling and optimization techniques for energy-aware and human-robot collaborative production planning. The knowledge developed will continue to be shared through academic courses, seminars, and student thesis projects at the University of Skövde. The results will also be integrated into ongoing research within the Virtual Engineering research environment, supporting long-term competence development in sustainable production planning and digital manufacturing.

Be passed on to other advanced technological development projects.
Several models and methods developed in PREFER, such as the multi-level optimization tool for machining lines and the task allocation models for collaborative assembly, are planned to be extended and adapted in follow-up projects. These include new initiatives focused on resilient manufacturing, intelligent scheduling, and energy-flexible production planning. The optimization frameworks and decision-support modules developed in PREFER serve as a foundation for further advanced research and collaborative development efforts, particularly in projects involving AI and multi-agent systems.

7.2 Publications

The project's results, findings, and developments have been published in a total of 10 scientific papers, 6 in international journals and 4 in peer-reviewed conference proceedings. The list of publications is provided below.

Journal publicaitons (6 papers):

1. Nourmohammadi, A., Fathi, M., & Ng, A. H. C. (2024). Balancing and scheduling human-robot collaborated assembly lines with layout and objective consideration. *Computers & Industrial Engineering*. https://doi.org/10.1016/j.cie.2023.109775
2. Mahmoodi, E., Fathi, M., Tavana, M., Ghobakhloo, M., & Ng, A. H. C. (2024). Data-driven simulation-based decision support system for resource allocation in Industry 4.0 and smart manufacturing. *Journal of Manufacturing Systems*. https://doi.org/10.1016/j.jmsy.2023.11.019
3. Fathi, M., Sepehri, A., Ghobakhloo, M., Iranmanesh, M., & Tsenge, M.-L. (2024). Balancing assembly lines with industrial and collaborative robots: Current trends

and future research directions. *Computers & Industrial Engineering*. https://doi.org/10.1016/j.cie.2024.110254

4. Beldar, P., Fathi, M., Nourmohammadi, A., Delorme, X., Battaïa, O., & Dolgui, A. (2025). Transfer line balancing problem: A comprehensive review, classification, and research avenues. *Computers & Industrial Engineering*. https://doi.org/10.1016/j.cie.2025.110913
5. Nourmohammadi, A., Arbaoui, T., Fathi, M, Dolgui A. (2025). Balancing human-robot collaborative assembly lines: a constraint programming approach Computers & Industrial Engineering. *Computers & Industrial Engineering*. https://doi.org/10.1016/j.cie.2025.111154
6. Petersen, J., Nourmohammadi, A., Fathi, M., Ghobakhloo, M., Tavana, M. (2025). Line Balancing for Energy Efficiency in Production: A Qualitative and Quantitative Literature Analysis. Computers & Industrial Engineering. *Computers & Industrial Engineering*. https://doi.org/10.1016/j.cie.2025.111144

Conference proceedings (4 papers):

7. Beldar, P., Nourmohammadi, A., Fathi, M., & Ng, A. H. C. (2024). A heuristic approach for flexible transfer line balancing problem. *Procedia CIRP*. https://doi.org/10.1016/j.procir.2024.10.219
8. Nourmohammadi, A., Fathi, M., Arbaoui, T., & Slama, I. (2024). Multi-objective optimization of cycle time and robot energy expenditure in human-robot collaborated assembly lines. *Procedia Computer Science*. https://doi.org/10.1016/j.procs.2024.01.126
9. Nourmohammadi, A., Beldar, P., Fathi, M., & Mahmoodi, E. (2024). Balancing and scheduling of sustainable flexible transfer lines. *IFAC-PapersOnLine*. https://doi.org/10.1016/j.ifacol.2024.09.224
10. Petersen, J., Nourmohammadi, A., Fathi, M., & Burmeister, C. (2024). Multi-objective optimization of transfer line balancing problem considering cycle time and energy expenditure. *Procedia CIRP*. https://doi.org/10.1016/j.procir.2024.10.255

8. Conclusions and future research

The PREFER project has successfully fulfilled its objectives by developing and validating optimization models, algorithms, and a decision-support tool for energy-efficient and digitally supported production planning in machining lines and human-robot collaborative assembly environments. Through this work, the project has contributed to the FFI

Sustainable Production sub-program by promoting resource-efficient and flexible production planning, advancing the digitalization of manufacturing processes, and supporting the integration of sustainability metrics into operational decision-making.

A key achievement of the project is the development of advanced mathematical models for line balancing and sequencing, which explicitly account for industrial constraints such as task precedence, sequence-dependent setups, machine compatibility, and multi-mode energy behavior. These models allow planners to optimize for multiple objectives, particularly minimizing both cycle time and energy usage. They have been extensively validated using real-world case studies and benchmark datasets.

The project also introduced a heuristic algorithm and a metaheuristic approach based on NSGA-II to address scalability for larger problem instances and enhance practical applicability. These methods deliver near-optimal results in significantly reduced computation times, supporting fast and effective planning in dynamic industrial settings.

The project developed MILP and CP-based models in collaborative assembly lines to support human-robot collaboration while minimizing energy use and maintaining productivity. These models account for human-robot task compatibility and robot energy consumption across operational states. Validation experiments showed that energy savings can be achieved without sacrificing production efficiency.

Another critical deliverable was developing a decision support tool that implements the optimization algorithms and provides a practical platform for planners to explore task assignments and production configurations. The tool supports multi-level optimization capabilities, can process input data from Excel files, and generates results in graphical (Gantt chart) and tabular formats.

Overall, the project outcomes align with the intended contributions and the goals of the FFI program. The planned deliverables were completed with acceptable technical maturity. In fact, the number and quality of scientific publications produced by the project exceeded initial expectations, reflecting strong knowledge creation and dissemination.

Future Research Directions

While the PREFER project has laid a foundation for digital and energy-aware production planning, several promising avenues for future research have emerged, as outlined below.

- Multi-agent planning and coordination: Future work can explore integrating the developed models into multi-agent systems that support decentralized planning and negotiation among different production agents (e.g., machines, robots, planners).
- AI-driven learning and prediction: Incorporating machine learning models to predict task durations, setup times, or energy profiles based on historical data could enhance model accuracy and adaptability.

- Real-time dynamic rescheduling: Building on the current tool, future versions could include capabilities for real-time adaptive planning in response to disturbances or changes in demand.
- Integration with industrial IoT: Linking the decision support tool with live data from sensors and production monitoring systems could enable automated feedback and closed-loop control of planning decisions.
- Extension to broader sustainability metrics: While this project focused on energy, future studies could incorporate broader sustainability indicators such as carbon footprint, waste minimization, or social sustainability measures.

In conclusion, the PREFER project has achieved its objectives and contributed to developing energy-efficient and intelligent planning tools. It has also provided a solid platform for ongoing research, education, and industrial innovation in smart and sustainable manufacturing.

9. Participating parties and contact persons

The PREFER project consortium consisted of the University of skövde as the academic partner and two industry partners, AB Volvo and Daloc AB.

Partner	Logo	Contact person
University of SKövde	UNIVERSITY OF SKÖVDE	Masood Fathi
AB Volvo	VOLVO	Andreas Telander
Daloc AB	DALOC Säkra dörrar.	Erik Henningsson