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Assessment of lean and green strategies by simulation of manufacturing systems in discrete production environments

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A R T I C L E I N F O

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A B S T R A C T

Manufacturing is a resource-intensive and costly endeavor, yet the impacts of implementing a combination of lean and green practices in a manufacturing facility can hardly be forecasted and have typically been simulated, optimized, and valuated independently. This paper identifies an approach for incorporating both lean and green strategies into a manufacturing system; from data collection to the valuation of a system. Furthermore, a case study is presented of part production in the automotive sector, in which the implementation of a tailored combination of lean and green strategies resulted in the reduction of approximately 10.8% of the production costs of a representative part.

1. Motivation

The cost of energy and resources are constantly increasing due to rising demand and limited supply. Furthermore, price trends can hardly be forecasted, so companies aim to successfully produce within large price ranges of energy and resources. One strategy to accommodate price fluctuations consists of passing markups to the customer. However, a price markup may require that improvements be made to the product. Alternatively, stable prices may be facilitated with increased production efficiency, which can be achieved by reducing resource consumption and improving the organization of the manufacturing system.

This paper focuses on the latter strategy and presents an approach for the assessment of lean and green strategies by simulation of manufacturing systems. The optimal combination of strategies depends on the industry and relevant processes. For instance, the effects of reducing batch size and solvent consumption differs between a paint shop and an assembly line in the automotive industry. Therefore, solutions must be tailored to accommodate specific applications in order to maximize impact.

2. Literature review

This literature review focuses on simulation-based approaches, a special case of quantitative assessment. A variety of approaches have been constructed to simulate the effects of applying lean methods in manufacturing, i.e., illustrating differences between a real and ideal state [1], examining their impact on performance indicators [2–4], and bundling simulation results in Cost-time profiles [5,6]. Research in green manufacturing spans a variety of scopes within the factory, from the development of energy models of production equipment [7,8] to the assessment of machine scheduling [9–11] and additional process planning [12,13] techniques on factory level energy consumption. Herrmann et al. developed a simulation to analyze the effects of implementing lean and green manufacturing strategies on energy consumption and costs [14].

Extensive research has been conducted in the fields of “simulating and optimizing” or “simulating and valuating” the application of lean and/or green strategies in manufacturing systems. However, the literature lacks an assessment methodology capable of simulating, optimizing, and valuating a manufacturing system’s performance indicators while using a tailored combination of lean and green strategies. Such an assessment methodology would allow companies to evaluate the effectiveness of strategies before spending funds to implement them on the shop floor.

3. Assessment of lean and green strategies by simulation

The following section describes an assessment methodology for simulating, optimizing, and valuating a manufacturing system’s performance indicators while using a tailored combination of lean and green strategies.

3.1. Modeling the current state

In order to set up a simulation model of a manufacturing system and subsequently optimize it, a variety of data needs to be gathered. The required data for each product variant that is manufactured can be categorized into factory and operational data, energy and resource requirements, and employee involvement.

All data needed to set up the discrete event simulation model of the current state can be measured on the shop floor or estimated with historical data. In order to create a simulation model capable of valuating the increase in a production system’s performance, installing multiple levels and building reusable modules is recommended. In a typical discrete production environment, one

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level displays the value stream while another level represents machine operations, e.g., tool changes, inspections, or setups. The value stream and machine operations may be linked by integrating inputs from equipment operators or other staff in the production area.

3.2. Optimizing the system with lean and green strategies

After gathering the data concerning the manufacturing systems' current status, lean and green strategies must be selected for the integration into the simulation model and their subsequent analyses, which can also be done by benchmarking or consulting experts. Benchmarking identifies the best-in-class values of comparable manufacturing systems within a company's network or in external enterprises. Expert consultation entails the acquisition of knowledge of specialized employees such as manufacturing engineers or technicians.

The following stages, defined according to maturity models in business processes and software development, are used to identify the company's progression in applying lean and green strategies: (1) initial, (2) planned, (3) defined, (4) measured, and (5) optimized. The use of stages requires that employees outline the current and desired state of the lean or green strategy. In order to indicate optimization intervals for the simulation, improvement potentials (e.g., the possible reduction in batch size or setup time) for each stage must be given. This can also be accomplished by means of expert consultation or benchmarking. Here, expert consultation results in the additional advantage of having a direct commitment to improving goals during implementation.

In a discrete event simulation model, manufacturing strategies may be parameterized with parameter or structural changes. Parameter changes are implemented by varying values within a pre-defined optimization interval. For example, a manufacturing system's setup time was reduced by 9.5% by applying stage 2 (planned) of the lean method: Single Minute Exchange of Die (SMED). Experts anticipate that further optimization would result in a 38% reduction in setup time compared to its original value without SMED (a 9.5% reduction at each stage). This corresponds to an optimization interval of [0.69; 1.00] relative to stage 2. Specifically, the value 1.00 represents the current value (stage 2), which accounts for the 9.5% improvement relative to the initial value (stage 1). The range of the interval of 0.31 represents the maximum amount to be saved when optimized (stage 5) relative to the current value (stage 2).

Modeling other strategies can require structural changes of the simulation model's internal logic. One such example, green scheduling, strives to lower resource consumption by utilizing machine tool scheduling techniques. Modifications to the machine tool schedule require changes of the simulation model's parameters affecting the scheduling sequence, therefore, a structural change is required. Tables 1 and 2 summarize the lean and green strategies during the operational phases of the factory and machine, respectively. The expected impact of each strategy and a means for modifying the simulation with parameter or structural changes are also presented.

Once suitable lean and green strategies are incorporated, the simulation model of the current state can be linked to parameter optimization software to increase the manufacturing system's performance. The following section of this article presents a cost minimization example. However, the assessment approach can also be utilized when pursuing alternative objectives or a multi-criteria target system, such as the minimization of energy, reduction of greenhouse gas emissions, or the use of a weighted scheme.

The objective function of the cost minimization problem consists of the overall variable costs of the analyzed production system (C_p) that can be tracked based on simulation results [10]. These costs are composed of five summands for all product variants *i*. In particular, opportunity costs ($C_{i,opportunity}$), material costs ($C_{i,material}$), machine costs ($C_{i,machine}$), inventory costs ($C_{i,inventory}$), and personnel costs ($C_{i,personnel}$).

$$\min C_p = \min \sum_{i=1}^{I} \{C_{i,opportunity} + C_{i,material} + C_{i,machine} + C_{i,inventory} + C_{i,personnel}\}$$

$$\text{s.t.} \quad x_1 \in [a_1, b_1], \quad x_2 \in [a_2, b_2], \quad \ldots, \quad x_\upsilon \in [a_2, b_\upsilon]$$

The objective function is executed subject to constraints that incorporate the lean and green strategies. More specifically, each lean or green strategy is considered a function *f*(*x*), with *x* either being a parameter change (i.e., $x \in [a_x;\ b_x]$ and $a_x,\ b_x \in R$) or a structural change (i.e., $x \in \{0;\ 1\}$).

Resource and energy consumption are included in material costs and machine costs, respectively. Machine costs result from multiplying the machine's hourly rate of machine *j* while pursuing an activity *h* ($mhr_{j,h}$) with the time of product variant *i* occupying machine *j* within the simulation period ($T_{i,j,h}$).

$$C_{i,machine} = \sum_{j=1}^{J} \left(\sum_{h=1}^{H} mhr_{j,h} \times T_{i,j,h} \right)$$

Energy costs are accounted for as part of the machine's hourly rates. They can be derived by summing the costs of electricity, gas, and fossil fuels, and multiplying consumption rates with prices and production lead times.

Table 1
A selection of lean and green strategies with direct impacts and approved modeling options for the factory operational phase.

Strategy	Green	Lean	Impact of strategy	Type of change to simulation
Batch reduction (e.g., one-piece flow)	q	x	Reduction in batch sizes; improvement in lead times; shorter waiting times	Parameter for batch sizes (e.g., [0.1; 1.0] if it can be reduced to 10%)
Change in production control system (e.g., introduction of kanban systems with supermarkets)	q	x	Less inventory; improvement in lead times; shorter waiting times	Structural changes depending on the production control system used
Defect reduction (e.g., total quality management [TQM])	x	x	Less re-work; less scrap; power reduction (planned amount of good parts to be produced faster)	Parameter for quality rate (e.g., [1.0; 1.1] if it can be improved by 10%)
Power load leveling	x		Reduced load on the electrical grid; reduced costs	
Total productive maintenance (TPM)	x	x	Improvement in availability; improvement in MTBF; reduction in MTTR	Parameters for availability, MTBF, MTTR
Process integration	x	x	Improvement in transportation; shorter waiting times	Structural changes within the factory layout (e.g., combined processes)
Green scheduling	x		Power reduction; potential effects on waiting and idle time depending on scheduling option chosen; affects makespan	Structural changes affecting the scheduling sequence, order, and machine selection

q: type of strategy depends on the parameters used; x: green and/or lean strategy.

Table 2
A selection of lean and green strategies with direct impacts and approved modeling options for the machine operational phase.

Strategy	Green	Lean	Impact of strategy	Type of change to simulation
Setup time reduction (e.g., single minute exchange of die [SMED])	x	x	Reduction in internal and external setup times	Parameter for setup times (e.g., [0.1; 1.0] if it can be reduced to 10%)
Tool path planning (i.e., air cutting time and cycle time reduction)	x		Reduction in energy consumption	
Production lead time reduction	x		Reduction in energy consumption	Parameter for cycle times (e.g., [0.1; 1.0] if it can be reduced to 10%)
Minimization of coolant use (i.e., dry cutting or cutting with MQL)	x		Reduction in energy consumption	
Process integration	x		Fewer tool changeovers; setup time reduction	Parameter for setup times; parameter for amount of tool changes
Use of more efficient components	x		Reduction in energy consumption	Parameter change

x: a green and/or lean strategy.

Parameter optimization software can solve optimization problems by using heuristics, e.g., an evolutionary algorithm. The results of the cost minimization problem exhibit the best design out of the simulation runs. The best design in this problem equates to the smallest cost within the range of the given optimization corridor. Therefore, reflecting the optimal combination of values within the optimization intervals of the considered lean and green strategies.

3.3. Economic evaluation and implementation plan

Based on the simulation results of the best design, revenues (R_{lean}) can be calculated. Revenues account for continuously attainable profit markups in the ideal state, generated by implementing a tailored combination of lean and green strategies. They can be traced back to cost reductions (CR_i) and increased sales volumes (IS_i) due to improvements in production processes, as well as waste reduction in terms of resource and energy consumption.

$$R_{lean} = \sum_{i=1}^{I} (CR_i + IS_i)$$

Cost reductions, achievable by improving processes or reducing waste, may be calculated by identifying potential areas of improvement, so called cost categories. For instance, inventory costs may be lowered with shorter production lead times. Additionally, the costs associated with machine downtime can be decreased by reducing the occurrence of failures and/or repair times, since these measures increase machine availability. When producing multiple product variants, the cost reduction of product variant i can be calculated by determining the difference between the cost categories in the real state ($C_{a,i,real}$) and ideal state ($C_{a,i,ideal}$), and multiplying it by the production volume in the ideal state ($N_{i,ideal}$).

$$CR_i = \sum_{a=1}^{A} (C_{a,i,real} - C_{a,i,ideal}) \times N_{i,ideal}$$

A critical cost category that needs to be considered is the continuous production cost ($PC_{i,Z}$) of both the real and ideal state of a product variant's production. The continuous production costs of state Z can be calculated based on the simulation results as follows:

$$PC_{i,Z} = [AC_{i,Z} + (CTI_{i,Z} \times IRR)] \times (1 + m)$$

where $AC_{i,Z}$ represents the value added within the manufacturing process, $CTI_{i,Z}$ the locked up capital multiplied with its internal rate of return, IRR, and m the estimated overhead to be added at the end of the manufacturing process, cf. [9]. Visualization of possible reductions in production costs can be achieved with the help of Cost-time profiles (CTPs).

4. Case study

The approach outlined in this paper was applied to an automotive company, which produces parts for powertrains. The powertrains are produced at a rate of approximately 230,000 units per year. Material flows from soft machining via the heat treatment department to hard machining. Suitable lean and green manufacturing strategies were selected from a portfolio during expert consultation interviews with the project partner.

The following lean strategies were modeled in the simulation: internal and external setup time reduction, quality rates increase, machine availability improvement, tool life extension, and batch size reduction. The green strategies that were assessed involved the washing machines, turning machines, hobbing and deburring processes. We sought to reduce the energy consumption of the washing machines by decreasing the applied water pressure. In order to lower the energy consumption of the turning machines, the utilization of energy efficient engines was considered. Lastly, we incorporated the potential use of process integration of the hobbing and deburring processes.

Tables 3 and 4 provide a summary of the lean and green strategies taken into consideration and their respective modeling options. They include the type of change to the discrete event simulation model, i.e., parameter or structural. In case of a parameter change, the corresponding optimization interval is provided, where the value of 1.0 represents the parameter's current value and the second value expresses the maximum possible improvement in the parameter compared to its current value. Structural changes are

Table 3
The selected lean strategies and their respective modeling options.

Strategy	Type of change to model	
Lean		
Internal setup time reduction	Parameter	[0.9; 1.0]
External setup time reduction	Parameter	[0.5; 1.0]
Quality rate improvement	Parameter	[1.0000; 1.0004]
Lifetime extension	Parameter	[1.0; 1.1]
Availability improvement	Parameter	[1.00; 1.04]
Batch size reduction	Parameter	[0.5; 1.0]

Table 4
The selected green strategies and their respective modeling options.

Strategy	Type of change to model	
Green		
Dimensioning to reduce pressure: washing machines	Parameter	[0.3; 1.0]
Use of energy-efficient engines: turning machines	Parameter	[0.914; 1.000]
Process integration: hobbing and deburring	Structural	Binary {0; 1}

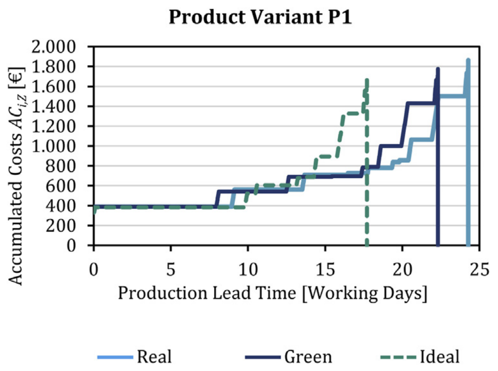

Fig. 1. Exemplary cost optimization results illustrated in a Cost-time profile.

either utilized or not. Thus, they are represented by a binary variable, and therefore adopt a value of 0 or 1.

Once relevant data was gathered and capable lean and green strategies were selected, a simulation model of the manufacturing system was setup in Plant Simulation® V9 by Siemens PLM Software in connection with the optimization software optiSLang® by Dynardo GmbH. The correctness of the model was verified and validated with the assistance of empirical data and production costs.

Cost-time profiles were created with batches consisting of an average of 55 units, while using averaged activity durations for each product variant. Additionally, a standard procedure for activities conducted at machines was assumed. The results of the manufacturing system's optimization showed that by implementing a tailored combination of lean and green strategies, 10.8% of the continuous production costs of an entity could be saved.

Fig. 1 illustrates the current, real state as a reference, as well as the ideal state that can be derived by implementing the tailored combination of strategies. Moreover, it shows the impact of utilizing green strategies assuming they are to be implemented first, cf. green state. Quantitatively, changes from the real state to the green state amount to 4.7% of the overall 10.8% savings in continuous production costs. The lean strategy with the highest positive impact is a batch size reduction of 50%. Out of the analyzed green strategies, the process integration of hobbing and deburring machines resulted in the greatest impact. Therefore, the company should first focus on these two strategies as was outlined in their recommended action plan.

5. Summary and outlook

This paper discussed a three-step approach to the proactive performance valuation of a manufacturing system affected by the application of lean and green strategies. In step one, the relevant data and abstraction levels needed to set up a discrete event simulation model were defined. The second step outlined potential lean and green methods that could be utilized within the company, as well as their modeling options in a simulation environment. Additionally, a program was described to actuate the optimization of the manufacturing system, for which a cost optimization example was utilized. The last step of the procedure covered the monetary evaluation of lean and green strategy implementation using Cost-time profiles. With the aid of Cost-time profiles, the most beneficial strategies can be identified resulting in an action plan for industrial companies. The approach was validated with the presentation of a case study of an automotive company in the last chapter.

Future collaborative research efforts will focus on including a broader variety of quantifiable green strategies within the factory, e.g., lighting, HVAC, or pressurized air consumption, and identifying a means of involving fixed costs in the decision-making process.

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