A Simulation-Based Methodology of Assessing Environmental Sustainability and Productivity for Integrated Process and Production Plans
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Abstract
With the increasing attention directed to sustainable manufacturing, systematic methodologies are needed for not only incorporating the traditional performance indicators such as cost and quality, but also environmental impacts during the production stage. This requires the selection of processes and process settings for the production of the design features to be optimal (i.e., higher productivity and lower negative environmental impact). Oftentimes, during process planning the improvement of one performance indicator (e.g., energy consumption) is at the cost of other ones (e.g., tool usage). In this paper, we introduce a systematic methodology that enables the combined assessment of environmental sustainability and productivity for integrated process and production plans using multi-objective optimization techniques. A case study of machining processes in a machine shop has been performed to demonstrate the proposed methodology.

Keywords: Simulation, Methodology, Activity Models, Process Plans, Production Plans

1 Introduction

Today, the increasing awareness for environmental sustainability issues is forcing product designers and manufacturers to be more prudent in shop floor decisions including process selections and sequencing. To assist in planning for the manufacturing processes, methods and tools are required for assessing the environmental, cost, and productivity impacts in the early stages of product and process design and production planning (Swift, K. & Booker, 2003). Process planning is influenced by production requirements for each job and available technology. While effective utilization of resources (e.g., machines and workforce) is the primary focus for production planning, a production plan has to satisfy both the strategic and operational goals. The challenge is to integrate process and production planning activities and to evaluate the impacts.

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Machining processes consume materials, energy, and cutting tools. The processes also use auxiliary materials such as coolants and lubricants. Additionally, the wastes from machining processes have a large negative environmental impact, with the extent of the impact influenced by the selected manufacturing methods and processes (Branker, December 2011). We note that a product can be realized through alternative operations and process settings that typically result in different environmental and productivity impacts. Process settings affect tool usage, lubricant usage, energy consumption, emissions, cost, and quality of the product. Additionally, the settings (i.e., cutting speed, depth of cut, and feed rate) determine how long it takes the part to be processed through the shop floor thereby affecting overall throughput and productivity. If information on environmental sustainability and productivity impacts are available to the designer, s/he can specify the product and associated processes with combined minimal impact. Modeling and simulation is an effective tool to help reduce manufacturing costs, improve quality, and shorten the time to market (Mclean & Leong, 2011). A simulation model of a production shop assists in investigating the combined impacts of process selection and process settings. The output analysis can be used to optimize the process according to the selected indicators. To help determine the optimum production plan for multiple objectives, a systematic methodology using simulation and process modeling is developed to assess and predict system performance for decision making. The first level of decision making is the process selection. The second level of decision making is the machine settings for the process selected.

Previous research work has developed heuristics for assessing the environmental sustainability of a given product, process, or system including those targeted for waste minimization, material efficiency, resource efficiency, and eco-efficiency (Guillen-Gosalbez & Grossmann, 2009). These studies aimed at guiding decision making for selecting machines, skills, and stock materials or components, and sequencing the processes that include cutting and forming processes, assembly processes, and finishing processes and inspection processes (Chau & Parkan, 1995). For example, in the machining process, the higher the speed or the depth of cut, the faster the part is produced. A production planner can decide to use high speed machining to reduce production time. It has been found for instance that the energy consumption decreases when the material removal rate increases because the time taken to remove a specific volume of material is reduced (Rajemi, Mativenga, & Jaffery, 2009) (Gutowski, Dahmus, & Thiriez, 2006). However, high speed setting has also been associated with excessive tool wear. As has been noted (Narita & Fujimoto, 2009), the relationship among these selections, on the one hand, and productivity and environmental impact, on the other, remains insufficiently investigated and understood.

This paper proposes an integrated and systematic simulation-based methodology that aids in assessing environmental sustainability performance and decision making for process planning for machining processes. Specifically, the detailed contributions within the methodology include (1) the relaxation of the design requirement of the production feature sequence selection, i.e., allowing fully defined, partially defined, and totally undefined feature sequencing; (2) application of Multiple-Criteria Decision Analysis (MCDM) for key performance indicators (KPIs); (3) the generation of generic data structures for the integrated process planning; and (4) a machining case study of a simple machine shop that produces grinding head shells has been performed to demonstrate the proposed methodology. Alternative sequencing of the processes and machine settings for the processes, called “scenarios” are analyzed to determine one with best performance according to selected KPIs.

The rest of the paper is organized as follows: section two describes the proposed methodology, section three presents a case study that demonstrates the methodology, and section four concludes the paper and discusses the future work.
2 Methodology

The different phases to realize any product are process planning, master production planning, capacity planning, and production scheduling. In each of these phases, important manufacturing planning decisions have to be made. On the shop floor, process and production planning determine how the products are routed and processed. This section describes the systematic methodology to study the environmental sustainability and productivity impacts when both process and production plans are integrated. The phases/steps of the activities in the methodology are shown in Figure 1. It has five phases: (1) goal and scope definition, (2) data structure generation, (3) model generation, (4) database description, and (5) result visualization and analysis. The following subsections will discuss the five phases in detail.

2.1 Goal and Scope Definition

This is the phase to define the goals and the scope of the study. For example, the goals of the study may be assessing the environmental sustainability performance and the challenge is determining optimal process and production plans. The scope of the study also needs to be clearly defined so that relevant system application, parameters, variables, and constraints are identified and modeled.
2.2 Data Structure Generation

The data structure generation phase is critical for performing effective performance analysis and providing decision guidance for process and production planning tasks. The planning strategies need to be analyzed to recognize a set of activities to be performed during manufacturing. The activities need to be represented as a flow model. The main activities are: (1) design conceptual model, (2) build activity models, and (3) build a data structure.

- Design Conceptual Models

A well-developed conceptual model is designed to enable stakeholders (e.g., production manager or quality engineer) highlight their concerns, provide the right level of abstraction of the problem, identify information exchanged between the model’s entities, and incorporate stakeholders’ objectives and constraints. A schematic representation is necessary to characterize the information flow and resource allocation for a specified goal (e.g., evaluating the environmental sustainability impacts of a specific process & production plans). For this purpose, several high-level layers have been designed: (1) the initial layer, design layer, describes the part’s features design information, including features’ forms, shapes’ complexities, dimensions, tolerances, and surface conditions; (2) the feature sequence layer presents alternative networks that describe features’ processing precedence during fabrication; (3) the material layer describes preferred material(s) based on the part’s functionalities and design requirements, in general, the selection of the material determines a set of processes that can be used to manufacture a part; (4) the process layer maps the material properties information and the geometrical knowledge for process selection; (5) the machine and tool layer describes the combinations of machines and tools that are capable of performing material type and design requirements (i.e., shape, dimensions, tolerance, and surface finish) based on all information from preceding layers; (6) the process setting layer inherits all the information that can be used to study the influences of the combination of material, process, machine, and tool on process setting options; and (7) performance indicator layer determines the best actions (i.e., selecting processes, resources, and their settings) to meet stakeholders’ objectives.

- Build Activity Models

Activity diagrams illustrate the activities that are performed when assessing system performance, the logical processing, and the data flow between activities by incorporating stakeholder inputs. Stakeholder-defined scenarios determine the required information. The data associated with these scenarios are key for carrying out an effective performance analysis and decision support.

- Build Data Structure Models

The developed conceptual and activity models provide the foundation for building a comprehensive data model that uses the manufacturing data for performance analysis. The primary challenge in developing such a data model is the ability to capture relevant data for representing precise planning strategies. An efficient data model will enable efficient data management and analysis (e.g., data preprocessing and storing), and the use or integration of various tools or programs for visualization and reporting. The main stages in building such a data model are:

1. Creating local databases and defining relevant data records from various data sources.
2. Integrating local data records to provide preferred information for designing planning strategies and evaluating their performance.
3. Building queries to support data transmission between existing records and manage their contents for different planning actions (e.g., calculate energy consumption for selecting a lathe machine at a specific setting).
2.3 Model Generation

The previous two phases enable the generation of analysis models for evaluating a variety of interrelated KPIs during product design stage. Simulation enables setting and modeling production scenarios, identifying the interactions among KPIs and their influence on stakeholders’ decisions. It provides stakeholders with actionable recommendations on the process and production plan performance.

Simulating the process and production planning scenarios to determine the impacts on different performance indicators could be time consuming because of extensive comparisons of many alternative planning options. The solution is to combine simulation with optimization models, mathematically formulate process and production planning activities, control variables, data, and constraints, for supporting various KPIs’ assessments. Mathematical programming models describe the minimization or maximization of the performance indicators’ objective functions subject to planning constraints. A feasible solution is an instantiation of values of decision variables that satisfy all the constraints. Decision variables, attributes, and constraints, recognized by the activity models and their related data are mapped from the data model. The procedure to select the best production and process plans with respect to various KPIs is shown in Figure 2. The details are discussed below.

- Identify Production Plan
  Based on part/product geometric features and their design constraints, different production plans are chosen as candidates to be studied to determine their impacts.

- Map Process Planning - Create Operation Method Matrix
  A variety of resources (machines and tools) may be required to perform a single operation (i.e., fabricate a single feature) of a given part design. The operation method matrix is constructed by identifying those candidate (feasible) resources that can fabricate the geometric features. The mapping of processes to resources is also influenced by product design specifications (e.g., material type, design geometries, and quality requirement).

- Design/select Process Plans
  Given that alternative resources can generate the same feature on a part, specifying the best set of resources (i.e., the optimal selection of process plan to transform a material stock into a finished part) is the main objective of our model. The resources and corresponding processes are specified in the operation method matrix. Before determining the process plan that has the optimal impact on the environmental sustainability and productivity, a range of process plan parameters (process settings) has to be assigned according to the operation method matrix entities. The relevant data are retrieved from the data model.

  Performance indicators are often conflicting such that improving one (e.g., energy consumption) diminishes the performance of another (e.g., cutting tool usage). In this research, we use multi-objective optimization to address this challenging problem. The proposed procedure, shown in Figure 2, illustrates how to evaluate process plans for combined environmental and productivity performance. It returns the best set of processes that has the optimal combined impacts. The main steps to employ the process plan evaluation procedure are:

1. **Assign initial settings:** Select initial process settings and map them to the operation method matrix, for all the processes, machines, and tools that are specified according to part design features.
2. **Perform linear normalization:** For each specified process plan, construct a score matrix to quantify the combined environmental and productivity impacts of the process operations. However, adding up different KPIs directly for aggregating the effects of different processes during process planning is difficult because the indicators are defined with different units. Normalization is required to make each parameter in a score matrix dimensionless and comparable. The following two cases of normalization can be used (Zavadskas, Zakarevicius, & Antucheviciene, 2006). First, if the target value of the performance indicator is “the-larger-the-
3. Perform pairwise comparisons: After normalizing the indicators, evaluating the relative importance of KPIs is necessary to prioritize various processes for performing a specific operation. Multiple Criteria Decision Making (MCDM) methods (Opricovic & Tzeng, 2002) rank the alternatives from the best to the worst, based on the stakeholder’s preferred structure. Analytic hierarchy process (AHP) (Saaty, 1980), one of the most commonly used ranking methods, uses pairwise comparisons to model the importance of each indicator relevant to the rest. The analyst can then form a square and a reciprocal pairwise comparison matrix. To ensure the preferences provided by the decision makers at the pairwise comparison matrix are valid and consistent, the consistency ratio to represent the consistency of the preferences entered by the decision is tested.

4. Calculate the total score matrix: After specifying the weights, the total score for combined environmental and productivity impacts for each process plan can be calculated by applying an additive form of value theory (Thevenot, Steve, Okudan, & Simpson, 2006). This theory is selected to rank the plans by obtaining a single score (i.e., aggregated score) for each process plan with regard to the targeted KPIs. To this end, a score matrix is constructed based on the normalized data and the subjective weight assigned to the KPIs. A process plan that has the highest score stands for the best choice for fabricating the designed part.

5. Validate score values: The knowledge gain by decision makers is how a change in process settings (e.g., cutting speed) can affect the outcome for each set of selected processes. The analyst can follow these steps described to obtain the best scores and return the associated processes and their settings.

2.4 Database

Data is available and can be retrieved to a local database from several different databases according to the requirements of the data structure models that are created in the data structure generation phase. The mapped local database provides the right data at the right time for decision making regarding the process and production plan selection. This requires the understanding of two aspects: (1) the context in which data is used in a process plan, production plan, or environmental impact and productivity assessments and (2) how the data should be collected and from where.

2.5 Result Visualization and Analysis

Based on the stated objective (e.g., select a process and production plan that achieves the optimal environmental sustainability and productivity performances), stakeholders have to identify related metrics that can be best used to measure the chosen objectives. Moreover, stakeholders need to
interact with the model by inputting user-specified data that are not available in any of the mapped databases or forming a query for certain information in a specific database. After the execution of the analysis models (simulation/optimization models), a recommended resources (process plan) and production plan that fit within the context of the identified KPIs’ objectives will be listed and displayed (i.e., data visualization). A Graphical User Interface (GUI) needs to be implemented as a platform to ease the communication for supporting different stakeholders’ queries.

Figure 2: Procedure for selecting production and process plans
3 Case Study

This case study is of a small machine shop that is designed to produce about 200 parts per day. A model of this shop is developed to demonstrate the proposed methodology. While remaining brief for space limitations, the five phases of the methodology are implemented as follows:

(i) The goals and scope

- Evaluating the impact of shop floor performance on environmental sustainability and productivity performance indicators.
- Examining the effectiveness and reliability of integrated process and production planning in obtaining optimal solutions.

This case study focuses on process plans for machining processes. The machine shop consists of a turning (lathe), a mill, a drill press, and a boring machine. A 250 grinding head shell shown in Figure 3 is used as the representative part. The objective of the study is to minimize costs (e.g., labor, cutting tool, and energy costs) and resource usage (e.g., the consumptions of material, energy, and water) while maximizing productivity.

![Custom-made 250 grinding head](image)

Figure 3: Custom-made 250 grinding head

(ii) Data structure generation: A data structure consisting of product and process information used to setup and/or control the process such as part geometry, KPIs, material properties, setup and operating instructions, quality plans and charting, and control programs is developed. Material information such as mechanical, chemical, thermal, and electromagnetic properties is also included.
Model generation: The model inputs include everything that enters or is consumed by the manufacturing process such as intermediate products, work-in-progress, raw materials, lubrication, energy, and disturbance factors that occur during production. The required manufacturing process operations for the part design are facing, grooving, threading, spot drilling, and drilling. A Discrete Event Simulation (DES) tool, Arena, is used to model the machine shop with a set of KPIs and OptQuest for Arena is used to optimize these KPIs. The simulation model of the shop is used to evaluate the impact of selected plans and processes, machine parameter settings on individual and/or combined KPIs. Within the Arena simulation tool, the main simulation modules are part arrival, data requirements for the part and process, the part routing to various machines, part exit, and statistics generation. We define manufacturing processes as events, parts as entities, buffers as queues, parts and processes specification data as attributes, and KPIs parameters as variables.

Database phase: Database includes information about product, process, resource, material, and associated properties. However, equipment, fixtures, and inspection gauges are not modeled in the simulation model. Table 1 shows the available machines capabilities to perform specific operations.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Facing</th>
<th>Grooving</th>
<th>Threading</th>
<th>Spot Drill</th>
<th>Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning (Lathe)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mill</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Drill Press</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Boring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 1: Machining capabilities

Result visualization and analysis: To optimize the processing sequence, three alternative approaches for determining the process sequencing for producing the part features, also called production plan scenarios, are chosen. Their impacts on environmental sustainability and productivity indicators are assessed.

In the first one, the parts are allocated to machines according to a predefined production plan that constrains and predetermines the features’ production sequence. In the second one, some of the constraints on the operational order of the features are relaxed on the operational order for some features, which is a partially defined production plan. In the third one, the undefined production plan is tested where planners do not have any restrictions on features precedence. For each of these three cases (fully defined, partially defined, and undefined), different process plans are tested and for each combination (production and process planning) impacts on various KPIs such as production time, cost, and energy consumption and carbon emission are evaluated. A total of nine experiments, the result of setting up of different combinations of production possibilities, have been conducted.

Once all the experiments are completed, all the KPIs are combined and used to optimize the multiple objectives. Optimization is performed by using MCDM and assigning different weighting factors to each indicator.

An energy model is built to analyze the energy consumption and carbon emission for selected production and process planning. The carbon emission rate is calculated from the energy consumption. The model analysis shows that adopting a partially defined or an undefined production plan decreases the required power to produce a given part about 59.223 % than the predefined scenario (as shown in Table 2). The significant reduction of cutting power consumption at these two production plans is due...
to the assignment of a turning process for fabricating all features for the given design (as indicated in Table 3).

<table>
<thead>
<tr>
<th>Production Plan</th>
<th>KPI / Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power Consumption (Kwh) / Energy Model</td>
</tr>
<tr>
<td>Predefined</td>
<td>515</td>
</tr>
<tr>
<td>Partially Defined</td>
<td>210</td>
</tr>
<tr>
<td>No Constraints</td>
<td>210</td>
</tr>
</tbody>
</table>

**Table 2:** Power consumption for different production plans

<table>
<thead>
<tr>
<th>Model Operation</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre_D*</td>
<td>515</td>
</tr>
<tr>
<td>Par_D*</td>
<td>210</td>
</tr>
<tr>
<td>NO_C*</td>
<td>210</td>
</tr>
</tbody>
</table>

Comparisons between the processes' settings over the three production plans for optimizing energy consumption are listed in Table 4 and Table 5. Furthermore, the percentages of processes applied, are also recorded in these tables.

<table>
<thead>
<tr>
<th>Production Plan/Model Type</th>
<th>CS/Turning (m/min)</th>
<th>CS/Milling (m/min)</th>
<th>CS/Press Drill (m/min)</th>
<th>CS/Boring (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predefined/Energy Model</td>
<td>129.991</td>
<td>124.47</td>
<td>51.6857</td>
<td>-</td>
</tr>
<tr>
<td>Partially Defined/Energy Model</td>
<td>152.116</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Undefined/Energy Model</td>
<td>152.116</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 4:** Cutting speed (CS) values for processes at different production plans
<table>
<thead>
<tr>
<th>Production Plan/Model Type</th>
<th>FR/Turning (mm)</th>
<th>FR/Milling (mm)</th>
<th>FR/Press Drill(mm)</th>
<th>FR/Boring (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predefined/Energy Model</td>
<td>40.772</td>
<td>16.993</td>
<td>17.311</td>
<td>-</td>
</tr>
<tr>
<td>% fabricated Operation</td>
<td>6.67 % facing, 100 % threading, 80 % spot drill, 80% drill</td>
<td>93.33% facing, 100% grooving</td>
<td>20% spot drill, 20 % drill</td>
<td>-</td>
</tr>
<tr>
<td>Partially Defined/Energy Model</td>
<td>45</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>% fabricated Operation</td>
<td>100% facing, 100% threading, 100 % spot drill, 100 % drill</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Undefined/Energy Model</td>
<td>45</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>% fabricated Operation</td>
<td>100% facing, 100% threading, 100 % spot drill, 100 % drill</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5: Feed rate (FR) values for processes at different production plans

4 Summary and Future Work

In this paper, we developed a systematic methodology for enabling the environmental sustainability and productivity performance assessment for integrated process and production plans at the machine cell level of manufacturing systems. Our methodology is aiming to help find out the best production and process plan out of all possible alternatives. A case study has been performed to demonstrate the methodology. The utilization of simulation and optimization techniques enables "what-if" analysis for the candidate scenarios and the selection of the best or preferred alternative from a finite set of alternate process and production plans. A DES tool is used to model the energy consumption of a shop floor. The simulation results indicate that using this methodology is more effective in encompassing all relevant parameters that have a significant impact on energy consumption. Moreover, sensitivity analysis is performed to determine the importance of the parameters (e.g., process parameter settings) on the energy consumption for different process and production alternatives.

Future research includes (1) applying this methodology to problems at other manufacturing system levels (e.g., enterprise and facility levels) and evaluating production activities’ impacts on process and production planning; (2) modeling and studying different performance indicators for environmental sustainability, productivity, agility, and quality; (3) performing more real world case studies for various manufacturing processes including primary shaping processes (e.g., casting and forming); secondary processes (e.g., bulk heat treatment); and assembly and test processes (e.g., joining and testing) to assess their processing and production planning interrelation impacts on selected KPIs; (4) classifying required information (e.g., potential operation sequences) supports process planning activities in local databases based on both product design specification and implementation as well as goal(s) of a manufacturing system; (5) implementing systems that automate the local database creation; and (6) researching and applying non-subjective method such as Knowledge-Based System (KBS) and Artificial Neural Network (ANN) to overcome the subjective disadvantages of the MCMD method when assigning weight for different KPIs.
Disclaimer

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