14th Annual International Conference on Industrial Engineering and Operations Management
Dubai, United Arab Emirates (UAE), February 12-14, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/AN14.20240267
Published: February 12, 2024

Economic Production Strategy Considering Energy Consumption and Recycling Constraints in Dry Machining

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Abstract

Industrial companies working to improve CNC (Computer Numerical Control) mechanical manufacturing machines face the challenge of integrating production decision aids that are adapted to the constraints associated with dry machining processes. This tool has a direct impact on productivity and the quality of the final product by helping to determine the most suitable production parameters for dry machining. The proposed study developed an economic production strategy that considers several parameters related to the production process and manufacturing system environment simultaneously. In fact, our goal is to minimize the total cost, including raw materials, production, recycling, and energy consumption costs. We consider two types of raw materials, Steel and Aluminum, and a random demand over a finite horizon dissociated into equal periods. A model has been developed to express the objective function, total cost, based on variable decisions. A numerical solving procedure and example are provided to demonstrate the model.

Keywords
Production, Dry machining, Raw material recycling, Energy consumption, Optimization.

1. Introduction and literature review

The success of manufacturing companies depends on their ability to oversee various functional aspects concurrently, such as production, raw material acquisition, and operational processes. In the realm of industrial operations, companies are always looking to improve efficiency and meet customer expectations in terms of service, delivery, quality and cost. while adhering to operational and environmental constraints. This imperative applies specifically to the machining industry, which is the main focus of our paper. The machining industry is complex and requires a comprehensive approach that goes beyond production considerations. It is essential to extend this approach to include raw material acquisition, environmental impact assessment, and the implementation of recycling activities. Due to the multifaceted nature of machining, companies operating in this sector face the challenge of managing costs and production quality while navigating the intricate interplay of environmental factors. Therefore, it is necessary to adopt an integrated strategy. Numerous researchers are interested in investigating the environmental impacts of production and energy consumption (Fratila 2013),(Cai et al. 2018), (Guerra-Zubiaga et al. 2018), (Sharma et al. 2022). Turki et al. (2018) developed optimal storage and production strategies for both manufacturers and remanufacturers, while investigating the impact of carbon trading prices and carbon caps on carbon emissions. In conjunction with carbon emissions, (Chang et al. 2017) concluded that the price of carbon and the savings in carbon emissions per remanufactured product will influence the manufacturer's decision to remanufacture.

Hajej and Rezg (2020) have introduced an integrated production-maintenance strategy that takes into account energy consumption. This approach considers random demand and a predetermined service level. The aim is to minimize the total average cost of inventory and production by determining the economic production lot size and the number of machines required. Moreover, an optimal maintenance plan is derived by considering how the resulting production plan affects system degradation and energy consumption. Then, some researchers have carried out a literature review to energy consumption (Bänsch et al. 2021), (Pawanr et al. 2022), (Hu et al. 2023).

Some researchers have recently investigated the relationship between mechanical production activities and system degradation. For example, Majdouline et al. (2022) treated especially the case of dry machining. They propose an integrated production-maintenance approach that allows the simultaneous consideration of various production parameters related to dry machining. These parameters primarily include cutting speed, production time and cost, preventive maintenance interval, quality standards and final product selling prices.

A distinctive aspect of this strategy, which operates within a finite time frame, is its ability to determine an optimal change in cutting speed at a given time, in conjunction with the scheduling of preventive maintenance intervals. The aim of this optimization is to maximize the total expected profit per unit of time.

Recently, Sun et al. (2023) have based their work on the case of specific cutting energy. In this sense, Rahman et al. (2020) presents a model for determining the Energy Consumption Allowance (ECA) of a workpiece, providing a reference value for each energy consumption step throughout the process. It shows great potential for determining the ECA of a machining system. The concept of an Energy Consumption Step (ECS) is introduced to provide a consistent way of describing different types of energy consuming operations in the machining of a workpiece, including various aspects such as machining ECS, transport ECS, storage ECS, various sub-ECS and basic ECS. In this frame some years before , Liu et al. (2016) developed a predictive model to quantify the relationships between material removal rate and specific energy, emissions and environmental impact. The study examined the emissions and environmental impact resulting from both the energy consumed by the machine tool and the embodied energy of the cutting tool.

Peng and Xu (2014),(Tuo et al. 2018) and (abdelaoui et al. 2023) reviewed energy-efficient machining systems and discussed the energy consumption associated with machining processes. It is worth noting that the cutting process itself accounts for only a small proportion of energy consumption, with the majority being attributed to losses, idling and auxiliary systems.

As mentioned earlier in this introduction, the paper focuses on machining, a widely used manufacturing system in the engineering industry, including sectors such as automotive, aerospace, and rail. Dry machining, which eliminates the need for cutting fluids, is becoming increasingly popular due to its environmental and health benefits. The shift towards eco-friendly products is driven by increasing consumer demand and government initiatives to reduce pollution. This has led industries to focus on minimizing their environmental impact. Additionally, turning, a widely used technique in industries such as automotive, aerospace and mold production, is subject to global economic competition. As a result, manufacturers are striving to improve product quality, increase productivity, and extend tool life. However, the use of specific cutting conditions can lead to phenomena such as machine tool chatter and tool wear, which can worsen the degradation of the machined surface and ultimately impact productivity. Therefore, it is highly advantageous to employ a predictive model to analyze the relationship between cutting conditions, energy consumption, recycling, and productivity.

In this paper, we have developed an economic production strategy for dry machining, considering simultaneously the production parameters, mainly cutting speed, production time and cost, as well as the energy consumed by the machines when machining two materials, Aluminum and Steel. The recycling activities are taken into account. The content of this paper is structured as follows: In Section 2, the problem in question and the overall strategy advocated for the optimization are described. Section 3 is devoted to the development of the mathematical model. Then, in Section 4, we present a numerical example intended to illustrate the application of the analytical model we have developed. Section 5 is dedicated to Numerical Results solved. Finally, Section 6 summaries our conclusions and outlines some perspectives.

2. Integrated strategy and problem statement

We consider a manufacturing system consisting of a CNC - Computer Numerical Control - mechanical manufacturing machines subject to random failures, which consisting in manufacturing products in two different materials (Aluminum and Steel) over a finite horizon H. The aim is to develop a production plan to meet random demand defined for each fixed periods in the horizon , followed by an economical maintenance strategy.

As illustrated in the figure below, the planning horizon is subdivided into H equal periods of duration Δt. Each period is divided into two subperiods. The first sub-period whose length is $\Delta t_{AL}(p)$ is devoted to the production of Aluminum parts in period p. The second sub-period is of length $\Delta t_{ST}(p)$, and is devoted to the production of Steel parts. It should be noted that the duration of these sub-periods evolves from one period to another but the period Δt stays constant: meaning that $\Delta t_{AL}(p) + \Delta t_{ST}(p) = \Delta t$. The production rates for Aluminum and Steel parts during each period are respectively $Pr_{AL}(p)$ and $Pr_{ST}(p)$.

The production rates depend to the durations of subperiods allowed to each type of raw material (Aluminum or Steel) and its speed cutting.

The Figure 1 illustrates the distribution of the planning horizon.

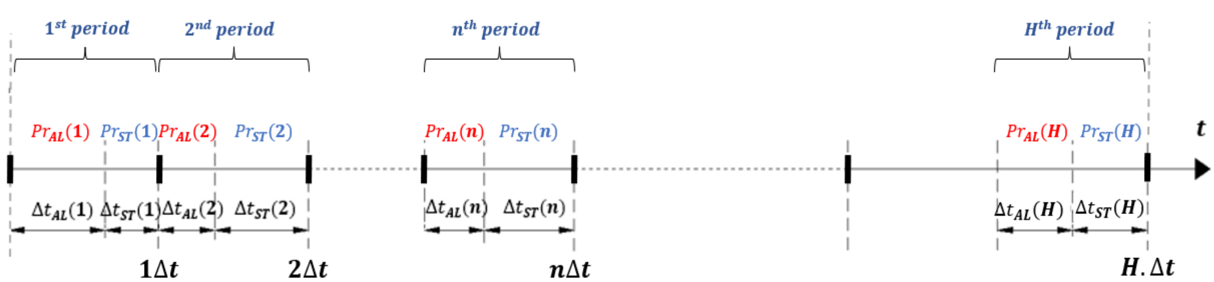

Figure 1. The integrated production-maintenance strategy over the finite time horizon H

Respecting the purposed random demand for each period, with minimizing a total cost including production, inventory, and recycling costs we will estimate the economical subperiods of production for each type of raw materials over the finite horizon. Then, taking the impact of the production of every type of raw material on the system degradation and relative preventive and corrective maintenance action, we established an economical preventive maintenance strategy.

The originality of our purposed work consists in considering the production process in all phases; from the choose of raw material characteristics to the output product in the special case of dry machining. In fact, the impact of the raw material characteristics on the production process (cutting speed, production cost) and the possible recycle activities related to the raw material are considered in order to establish an economical production plan. The economic plan is obtained by minimizing a total cost including raw materials, production, inventory, energy and recycling costs.

3. Production model

3.1. Notation

To develop this model, the following notations are used (Table 1):

Table 1. Product Model

Δt	: Length of production periods
α_{AL}	: Percentage of material machined in the production of an Aluminum part
W_{AL}	: Weight of one Aluminum part
W_{ST}	: Weight of one Steel part
RMC_{AL}	: Unit cost of raw materials for Aluminum parts
RMC_{NewAL}	: Cost of raw materials for Aluminum parts
RMC_{RecyAL}	: Cost of recycled raw material for Aluminum parts
RMC_{ST}	: Unit cost of raw materials for Steel parts
$TRMC$	: Average total cost of raw materials (Aluminum and Steel)
C_e	: Energy unit cost
Pc_{AL}	: Cutting power required for machining Aluminum parts
Pc_{ST}	: Cutting power required for machining Steel parts
f	: Machining system feed speed [mm/rev]
a_p	: Passing depth [mm]
k_c	: Specific cutting pressure [N/mm^2]
v_c	: Cutting speed [m/min]
$TEnrgC$	: Average total energy costs for machining Aluminum and Steel parts
$S_{AL}(p)$	: Stock levels of Aluminum parts at end of period p
$S_{AL}^{M}(p)$	: Stock level of Aluminum parts at the end of the first sub-period of the period p.
$d_{AL}(p)$	: Average demand for Aluminum parts at the end of the period p
UCs_{AL}	: Unit cost of storing an Aluminum part
$CS_{AL}(p)$	: Cost of storing an Aluminum part over the period p
$S_{ST}(p)$	: Stock levels of Steel parts at end of period p
$d_{ST}(p)$	: Average demand for Steel parts at end of period p
$TStc$	: Average total storage costs for Aluminum and Steel parts
SC_{AL}	: Unit shortage costs for Aluminum parts
SC_{ST}	: Unit shortage costs for Steel parts
$TShc$	: Average total shortage costs for Aluminum and Steel parts
$TPC(.)$	: Average total production costs
$Pr_{AL}(p)$	: Quantity of Aluminum parts produced during the period p
$Pr_{ST}(p)$	: Quantity of Steel parts produced during the period p
$\Delta t_{ST}(p)$	: Duration of sub-period of production of Aluminum parts in the period p

The decision variables:

$\Delta t_{AL}(p)$: Duration of sub-period of production of Aluminum parts in the period p

3.2. Production costs

3.2.1. Average total production cost

The average total production cost can be expressed as follows:

$$
\begin{aligned}
&\boldsymbol{TPC(Pr_{AL}(p), Pr_{ST}(p))}\\
&\quad = \sum_{p=1}^{H}[\boldsymbol{RMC_{AL}} \times \boldsymbol{Pr_{AL}(p)} \times \mathbf{W}_{AL}] + \sum_{p=1}^{H}[\boldsymbol{RMC_{ST}} \times \boldsymbol{Pr_{ST}(p)} \times \mathbf{W}_{ST}]\\
&\quad + \sum_{p=1}^{H}[\boldsymbol{Pc_{AL}} \times \Delta \boldsymbol{t_{AL}(p)} + \boldsymbol{Pc_{ST}} \times \Delta \mathbf{t_{ST}(p)}] \times \boldsymbol{C_e}\\
&\quad + \mathbf{UCs_{AL}}\\
&\quad \times \sum_{p=1}^{H}\Big[\mathbf{S_{AL}(p-1)} \times \Delta \mathbf{t_{AL}(p)} \times \mathbf{1}_{S_{AL}(p-1)>0}\\
&\quad + \boldsymbol{S_{AL}^{M}}\mathbf{(p)} \times \Delta \mathbf{t_{ST}(p)} \times \mathbf{1}_{S_{AL}^{M}(p)>0}\Big]\\
&\quad + \boldsymbol{Cs_{ST}} \times \sum_{p=1}^{H}\big[\boldsymbol{S_{ST}(p)} \times \Delta \mathbf{t_{ST}(p)} \times \mathbf{1}_{S_{ST}(p-1)>0}\big]\\
&\quad + \boldsymbol{SC_{AL}} \times \sum_{p=1}^{H}\big[|\boldsymbol{S_{AL}(p)}| \times \mathbf{1}_{S_{AL}(p)<0}\big]\\
&\quad + \boldsymbol{SC_{ST}} \times \sum_{p=1}^{H}\big[|\boldsymbol{S_{ST}(p)}| \times \mathbf{1}_{S_{ST}(p)<0}\big]
\end{aligned}
\tag{1}
$$

We note that his cost is composed of four costs parts below:

- Average total cost of raw materials.
- Average total energy cost.
- Average total storage cost.
- Average total shortage cost.

The expression of each part is developed in the next sections.

3.2.2. Average total cost of raw materials

Aluminum parts are machined from two types of material: raw material and recycled material. The raw material is purchased from an external supplier. On the other hand, the material recycled internally is obtained from chips (leftover material after machining) from machined parts. It is considered that each part consists of a percentage α_{AL} of recycled material and the rest of raw material. On the other hand, Steel parts are produced from a single type of material.

This process is illustrated in the Figure 2

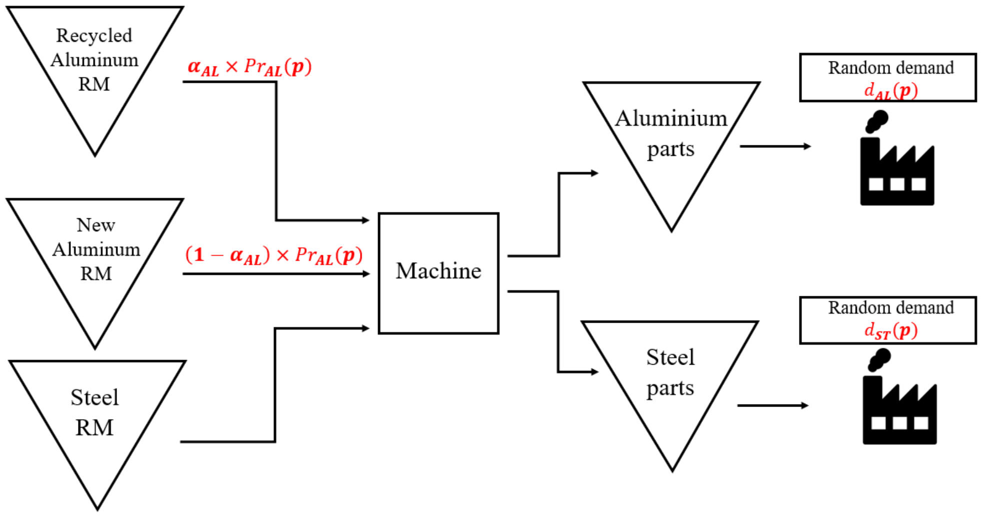

Figure 2. Machining process for Aluminum and Steel parts

The average total raw material cost function over the planning horizon $H \times \Delta t$ is therefore expressed as:

$$TRMC = \sum_{p=1}^{H}[RMC_{AL} \times Pr_{AL}(p) \times W_{AL}] + \sum_{p=1}^{H}[RMC_{ST} \times Pr_{ST}(p) \times W_{ST}] \tag{2}$$

The cost of raw material (per Kg) to produce an Aluminum part is represented by the equation below:

$$RMC_{AL} = RMC_{RecyAL} \times \alpha_{AL} + RMC_{NewAL} \times (1 - \alpha_{AL}) \tag{3}$$

We recall that:

α_{AL} : Percentage of material machined in the production of an Aluminum part
RMC_{NewAL} : Cost of raw materials for Aluminum parts
RMC_{RecyAL} : Cost of recycled raw material for Aluminum parts

3.2.3. Average total energy cost

The average total energy cost is expressed by the following function:

$$TEnrgC = \sum_{p=1}^{H}[Pc_{AL} \times \Delta t_{AL}(p) + Pc_{ST} \times \Delta t_{ST}(p)] \times C_e \tag{4}$$

To develop this model, we considered that the energy cost depends on the cutting power required (P_c) during a drying operation. The equation below will be used to calculate (P_c) :

$$P_c = f \times a_p \times k_c \times v_c \tag{5}$$

A cutting power Pc_{AL} and Pc_{ST} in [W] is required to produce an Aluminum part and Steel part respectively on a machine tool. The power Pc_{AL} and Pc_{ST} required during the turning (machining) operation, can be obtained as follows:

$$Pc_{AL} = f_{AL} \times a_{pAL} \times k_{cAL} \times v_{cAL} \tag{6}$$

$$Pc_{ST} = f_{ST} \times a_{pST} \times k_{cST} \times v_{cST} \tag{7}$$

3.2.4. Average total storage cost

Based in the Figure 3, the average total cost of stocking Aluminum parts and Steel parts over the planning horizon $H \times \Delta t_{ST}$ is expressed by:

$$\begin{aligned} TStc \ = \ \mathbf{UCs_{AL}} \times \sum_{p=1}^{H} \Big[\mathbf{S_{AL}(p-1)} \times \Delta \mathbf{t_{AL}(p)} \times \mathbf{1}_{S_{AL}(p-1)>0} \\ + S_{AL}^{M}(\mathbf{p}) \times \Delta \mathbf{t_{ST}(p)} \times \mathbf{1}_{S_{AL}^{M}(p)>0} \Big] \\ + \ Cs_{ST} \times \sum_{p=1}^{H} (S_{ST}(p) \times \Delta \mathbf{t_{ST}(p)} \times \mathbf{1}_{S_{ST}(p-1)>0}) \end{aligned} \tag{8}$$

The term "$1_{S_{ST}(p)>0}$" is equal to 1 if the quantity of Steel parts stored in period p is positive and equal to 0 otherwise. The term "$1_{S_{AL}^{M}(p)>0}$" is equal to 1 if the quantity of Aluminum parts stored between during $\Delta t_{ST}(p)$ is positive and equal to 0 otherwise.

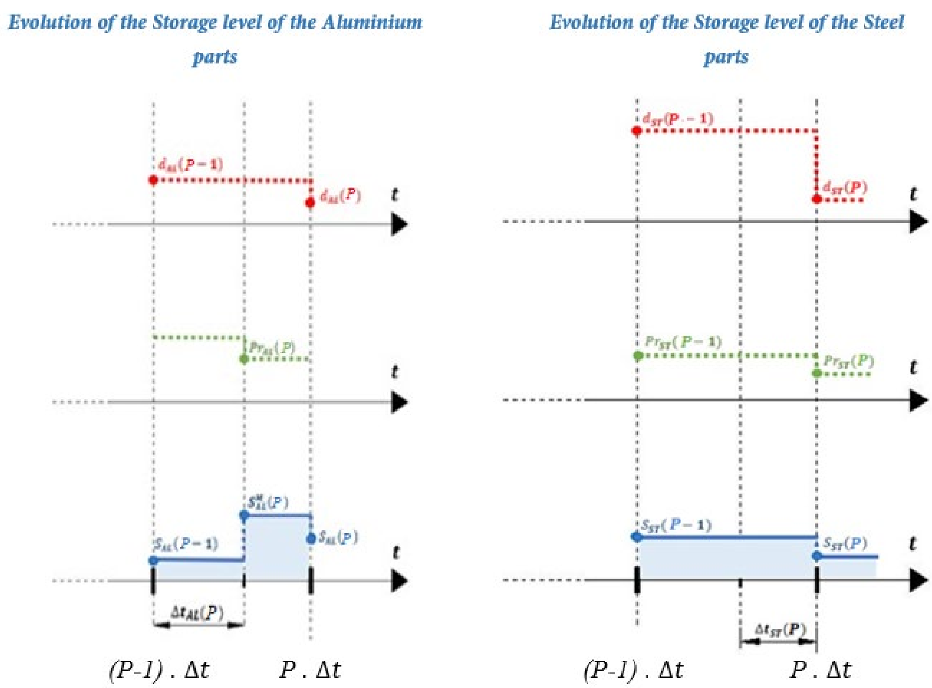

Figure 3. Evolution of the Storage level of the Aluminum and Steel parts

Figure 3. illustrates the evolution of production, demand, as well as the inventory status of Aluminum and Steel parts over the $H \times \Delta t$ planning horizon.

3.2.5. Average total shortage cost

Based on the Figure 3, the average total shortage cost function for Aluminum and Steel parts over the entire planning horizon $H \times \Delta t$, is expressed as follows:

$$TShc = SC_{AL} \times \sum_{p=1}^{H} \left[|S_{AL}(p)| \times \mathbf{1}_{S_{AL}(p)<0} \right] + SC_{ST} \times \sum_{p=1}^{H} \left[|S_{ST}(p)| \times \mathbf{1}_{S_{ST}(p)<0} \right] \tag{9}$$

3.2.6. Economic production planning

To determine the economic production plan, we need to minimize the average total production cost function in order to determine the optimal production subperiods for every type of raw materials such us Δt_{AL} and Δt_{ST}. The problem will be formulated as follows:

$$\boldsymbol{Min}\Bigg[\sum_{p=1}^{H}[\boldsymbol{RMC_{AL}} \times \boldsymbol{Pr_{AL}(p)} \times \mathbf{W}_{AL}] + \sum_{p=1}^{H}[\boldsymbol{RMC_{ST}} \times \boldsymbol{Pr_{ST}(p)} \times \mathbf{W}_{ST}]$$
$$+ \sum_{p=1}^{H}[\boldsymbol{Pc_{AL}} \times \Delta \boldsymbol{t_{AL}(p)} + \boldsymbol{Pc_{ST}} \times \Delta \mathbf{t_{ST}(p)}] \times \boldsymbol{C_e}$$
$$+ \mathbf{UCs_{AL}} \times \sum_{p=1}^{H}\left[\mathbf{S_{AL}(p-1)} \times \Delta\mathbf{t_{AL}(p)} \times \mathbf{1}_{S_{AL}(p-1)>0} + \boldsymbol{S_{AL}^{M}}\mathbf{(p)} \times \Delta\mathbf{t_{ST}(p)} \times \mathbf{1}_{S_{AL}^{M}(p)>0}\right] \quad (10)$$
$$+ \boldsymbol{Cs_{ST}} \times \sum_{p=1}^{H}\left[\boldsymbol{S_{ST}(p)} \times \Delta\mathbf{t_{ST}(p)} \times \mathbf{1}_{S_{ST}(p-1)>0}\right]$$
$$+ \boldsymbol{SC_{AL}} \times \sum_{p=1}^{H}\left[|\boldsymbol{S_{AL}(p)}| \times \mathbf{1}_{S_{AL}(p)<0}\right] + \boldsymbol{SC_{ST}} \times \sum_{p=1}^{H}\left[|\boldsymbol{S_{ST}(p)}| \times \mathbf{1}_{S_{ST}(p)<0}\right]\Bigg]$$

Under the following constraints:

$$\begin{cases} Pr_{AL}(p) \leq Pr_{AL}max \\ Pr_{ST}(p) \leq Pr_{ST}max \\ S_{AL}^{M}(\mathrm{p}) = S(p-1) + Pr_{AL}(p) \\ S_{AL}(p) = S_{AL}^{M}(\mathrm{p}) - d_{AL}(p) \\ S_{ST}(p) = S_{ST}(p-1) + Pr_{ST}(p) - d_{ST}(p) \end{cases}$$

We recall that the decision variables that will minimize the average total cost of production are: $\Delta \mathrm{t_{AL}(p)}$ et $\Delta \mathrm{t_{ST}(p)}$.

4. Numerical example

The solution procedure was tested extensively on a large number of numerical examples, each with different input parameters. Below, we present the set of input data (Table 2.) that were specifically chosen while adhering to practical parameters.

Table 2. Numerical data

Data related to the production activity	
Machining process	Turning
Work material	*42CrMo4* Steel (a medium carbon Steel close to an *AISI 4142* Steel) *et AlSi12Cu Aluminum*
RMC_{AL}	120 €
RMC_{ST}	70 €
W_{AL}	2.2
W_{ST}	4
f_{AL}	*0.1 mm/tr*
a_{pAL}	*4 mm*
k_{cAL}	*800 Mpa*
v_{cAL}	*900 m/s*
f_{ST}	*0.15 mm/tr*
a_{pST}	*1.5 mm*
k_{cST}	*2000 Mpa*
v_{cST}	*400 m/s*
C_e	0.2276 €
UCs_{AL}	1.5
UCs_{ST}	2.5
SC_{AL}	17
SC_{ST}	21

$S_{AL}(p)$	120
$S_{ST}(p)$	100
$Pr_{AL}(p)$	450
$Pr_{ST}(p)$	300
Δt	2 months
H	30 months

Random demand

$dAL_1 = 320$	$dAL_{11} = 320$	$dAL_{21} = 811$	$dST_1 = 250$	$dST_{11} = 510$	$dST_{21} = 500$
$dAL_2 = 130$	$dAL_{12} = 136$	$dAL_{22} = 131$	$dST_2 = 102$	$dST_{12} = 124$	$dST_{22} = 130$
$dAL_3 = 460$	$dAL_{13} = 555$	$dAL_{23} = 350$	$dST_3 = 540$	$dST_{13} = 636$	$dST_{23} = 432$
$dAL_4 = 240$	$dAL_{14} = 131$	$dAL_{24} = 140$	$dST_4 = 120$	$dST_{14} = 243$	$dST_{24} = 119$
$dAL_5 = 345$	$dAL_{15} = 720$	$dAL_{25} = 426$	$dST_5 = 415$	$dST_{15} = 318$	$dST_{25} = 222$
$dAL_6 = 112$	$dAL_{16} = 142$	$dAL_{26} = 130$	$dST_6 = 130$	$dST_{16} = 226$	$dST_{26} = 739$
$dAL_7 = 600$	$dAL_{17} = 511$	$dAL_{27} = 218$	$dST_7 = 625$	$dST_{17} = 116$	$dST_{27} = 115$
$dAL_8 = 210$	$dAL_{18} = 133$	$dAL_{28} = 626$	$dST_8 = 210$	$dST_{18} = 629$	$dST_{28} = 620$
$dAL_9 = 423$	$dAL_{19} = 329$	$dAL_{29} = 152$	$dST_9 = 104$	$dST_{19} = 530$	$dST_{29} = 150$
$dAL_{10} = 164$	$dAL_{20} = 247$	$dAL_{30} = 754$	$dST_{10} = 948$	$dST_{20} = 103$	$dST_{30} = 360$

5. Numerical Results and Discussion

Adopting the solving method presented in the previous section and by the help of Mathematica software we obtained the results presented in Table 3. These results expressed the subperiods and the quantity of production for each type of raw material Steel and Aluminum to meet the random demands for each period over the finite horizon.

Table 3. Numerical results

P	$\Delta t_{AL}(p)$	$\Delta t_{ST}(p)$	$Pr_{AL}(p)$	$Pr_{ST}(p)$	P	$\Delta t_{AL}(p)$	$\Delta t_{ST}(p)$	$Pr_{AL}(p)$	$Pr_{ST}(p)$
1	0,35	1,65	158	495	16	0,16	1,84	72	552
2	0,84	1,16	378	348	17	1,80	0,20	810	60
3	1,10	0,90	495	270	18	0,15	1,85	68	555
4	0,27	1,73	122	519	19	0,36	1,64	162	492
5	1,30	0,70	585	210	20	1,39	0,61	626	183
6	0,12	1,88	54	564	21	1,17	0,83	527	249
7	0,96	1,04	432	312	22	0,14	1,86	63	558
8	0,55	1,45	248	435	23	1,28	0,72	576	216
9	1,83	0,17	824	51	24	0,15	1,85	68	555
10	0,18	1,82	81	546	25	1,63	0,37	734	111
11	0,35	1,65	158	495	26	0,14	1,86	63	558
12	0,15	1,85	68	555	27	0,24	1,76	108	528
13	0,94	1,06	423	318	28	0,97	1,03	437	309
14	0,54	1,46	243	438	29	1,75	0,25	788	75
15	1,47	0,53	662	159	30	1,40	0,60	630	180

To demonstrate the relevance of the developed model, a sensitivity study will be presented below in Figure 4:

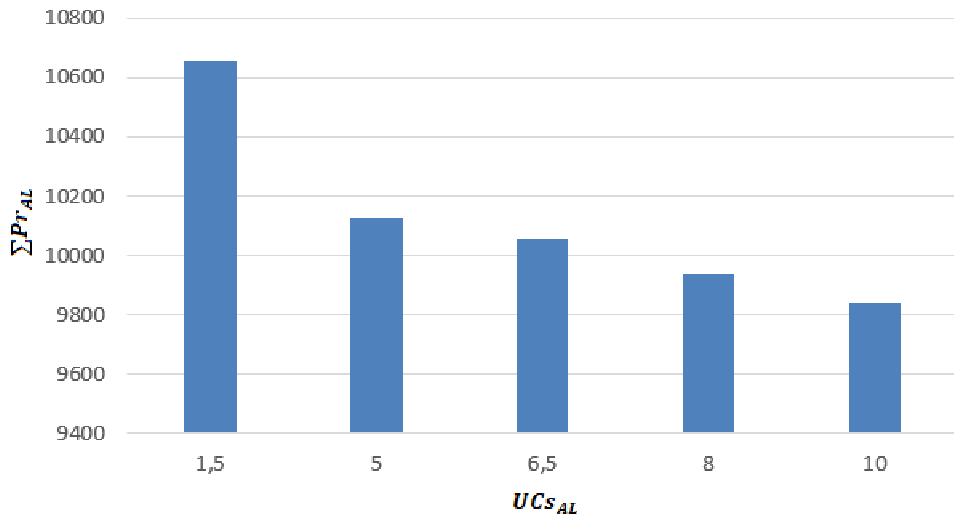

Figure 4. Evolution of production quantities according to UCs_{AL}

It is evident that an increase in the storage cost of Aluminum parts results in a decrease in the quantities produced over the planning horizon. This is a logical outcome as fewer parts will be stored.

6. Conclusion

Our challenge in the proposed study is to find an economic production plan that takes into account the dry machining production process, from the raw material selection step to the quality of the final product. In fact, we propose that we have to satisfy a random demand distributed over periods in a finite horizon. It is possible to satisfy the demand by using one of two types of raw material (Aluminum and Steel), which differ in terms of their physical characteristics. This difference has an impact on several economic and technical aspects, such as the cost of the raw material, the stocks of the finished product, the recycling costs, the cutting speed and the energy consumption. It is easy to see that there is a relationship between these aspects. The impact of these aspects and their relationship are taken into account when drawing up an economic plan. The production plan is based on the best combination between the two types of raw materials (Aluminum and Steel); that is, we determine the duration of two sub-periods. (for Aluminum $\Delta t_{AL}(p)$ and for Steel $\Delta t_{ST}(p)$ for each period over the finite horizon. These sub-periods are determined by minimizing a total cost integrating production, energy consumption, inventory and raw material acquisition. A numerical example is developed to prove the developed mathematical model.

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