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Optimization for sustainable manufacturing based on axiomatic design principles: a case study of machining processes

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A B S T R A C T

Despite being a wasteful process, machining is often regarded as an important manufacturing method due to the fact that it is a flexible and economic process. However, in order to gain more cost-saving and enhanced environmental performance, sustainability principles have to be incorporated into machining technologies. A step-wise optimization procedure is proposed based on axiomatic design (AD) principles for identifying an optimized sustainable manufacturing solution that comprises combinations of minimum and maximum levels obtainable within the constraints involved (cutting condition, performance and sustainability). A case study involving three alternative processes (namely conventional machining, high pressure jet-assisted machining, and cryogenic machining) is presented for demonstrating the application of the proposed approach, which indicated that the suggested procedure is able to facilitate an optimization process by varying the design parameters (DPs) within a particular sequence. In the case study, a hybrid model consisting of crisp and fuzzy AD analysis techniques was also used for analysing the sustainability performances of the processes being considered. The hybrid model is able to point out the most viable machining process that satisfies all the sustainable functional requirements (FRs) by using information content for indication purposes.

A R T I C L E   I N F O

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1. Introduction

Machining is a material removal process that usually involves the cutting of metals using a variety of cutting tools. Therefore, being a process that removes material, machining is inherently wasteful owing to the use of raw materials and energy. Nonetheless, due to their high dimensional accuracy, process flexibility and cost-effectiveness in producing parts, machining processes can be particularly useful [1]. In the developed world, it is estimated that machining processes contribute about 5 % of the total GDP. Furthermore, the importance of machining is anticipated to increase even further due to shorter product cycle and more flexible manufacturing systems induced by economic factors [2].

Machining processes constitute a major manufacturing activity that contributes to the development of the worldwide economy [3]. By implementing sustainability principles in machining technologies, end-users can potentially save money and enhance environmental performance even if the production remains in the same range or reduces [4, 5]. To make a manufacturing process sustainable, the following six factors (together with their desired levels) as shown in Table 1 are generally regarded as significant [6]. These six factors can be divided into two broad categories i.e. sustainability factors for safety, health and environment (S_{SHE}) and operational sustainability factors (S_{OP}) which comprises machining costs, energy consumption and waste management [2]. Alongside sustainability measures, machining performance (in terms of surface roughness, part accuracy and so on) is also an important consideration in designing a product for machining and in subsequent process planning operations [7]. Hence, a general workflow of optimization method for process sustainability assessment of machining processes has been previously proposed. This proposed method (as shown in Fig. 1) aims to make a trade-off among performance and sustainability measures, and therefore to provide the optimal combinations of operating parameters and to propose ways of enhancing and improving sustainability level [6]. It requires a hybrid modelling technique that comprises both numerical analysis and nondeterministic means such as fuzzy logic to scientifically quantify the influence of each sustainability parameter. After that, the modelled production process can be optimized to attain desired level of sustainability with respect to constraints imposed by all involved variables. Although it serves as a comprehensive guideline, the proposed workflow does not provide a step-wise procedure that facilitates the optimization process.

Recently, research works have been carried out to address sustainability assessment / comparison on manufacturing processes. A macro-level (excludes impact of cutting tools and cutting fluids) environmental comparison has been done on flood machining and near-dry machining using gear milling as a case study. The conducted study has a disadvantage that the analysis performed is valid only for the machining process of the considered part. The problem can be solved by creating a general model of analysis to be valid for any machining process [8]. Lifecycle assessment approach was also used to compare alternative machining processes with the aim of convincing the industry of the merits of sustainable machining technologies [9]. Experimentally, conventional machining and its alternative processes (e.g., high pressure jet-assisted machining and cryogenic machining) have been examined based on their machining costs, cutting fluid usage and energy consumption [3]. Nonetheless, the last two approaches do not involve combination of numerical and fuzzy models that can deal with human thought and are therefore not adequate in supporting decision-making process.

This paper presents a case study that demonstrates the selection of optimized manufacturing process with the help of a hybrid model based on axiomatic design principles. Section 2 briefly covers the basic principles of axiomatic design, while Section 3 discusses the formation of design equation for the optimization problem. The subsequent section gives a detailed presentation about the case study and the results are discussed in Section 5. Lastly, Section 6 provides concluding remarks for this paper.

Table 1 Measurable sustainability factors in machining processes and their desired levels [6]

Measurement factor	Desired level
Energy consumption	Minimum
Environmental friendliness	Maximum
Machining costs	Minimum
Operational safety	Maximum
Personnel health	Maximum
Waste reduction	Maximum

2. Principles of axiomatic design

Axiomatic design (AD) system is a design model based on product attribute in which two axioms are utilized for design. The first axiom highlights the necessity to maintain independence of functional requirements (FR) while the second one is to minimize the information necessary to meet the FRs [10]. In other words, a good design should fulfil its various FRs independently and simply [11].

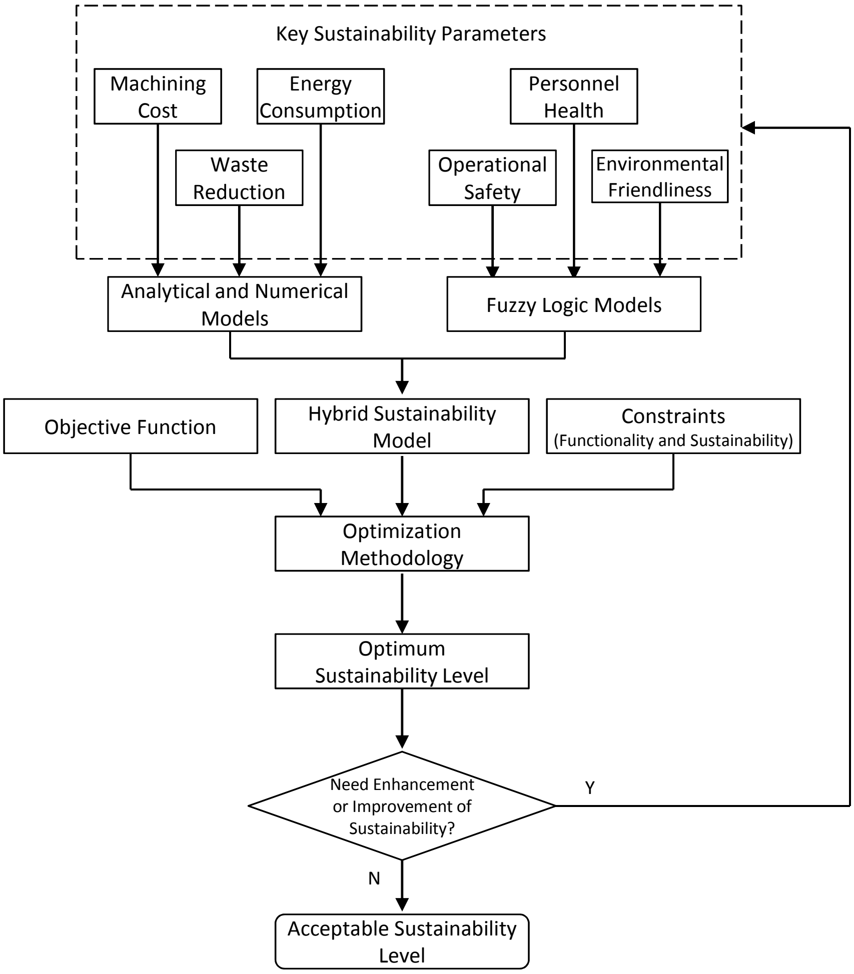

Fig. 1 Flowchart showing the proposed optimization method for process sustainability assessment of machining processes [6]

The relationship between functional requirements and design parameters (DPs) can be expressed mathematically as follows where {**FR**} is the functional requirement vector and {**DP**} signifies the design parameter vector:

$$\{\mathrm{FR}\}=|\mathrm{A}|\{\mathrm{DP}\} \tag{1}$$

The type of design being considered is defined by the structure of |**A**| matrix. To fulfil the independence axiom, |**A**| matrix of a design should be uncoupled or decoupled.

According to the information axiom, the best design among all design alternatives that satisfy independence axiom is the one that has the smallest information content (I_i). As represented by the following equation, I_i can be related to p_i, which is the probability of satisfying the given functional requirement FR_i, and the relationship between I_i and p_i is inversely proportional:

$$I_i = \log_2\left(\frac{1}{p_i}\right) \tag{2}$$

The probability of having a successful design is governed by "design range" and "system range". Design range is a designer-specified range of tolerance whereas system range means the capability of the system in delivering what the designer desires to achieve. Acceptable design solution exists in the region where design range and system range overlap as depicted in Fig. 2 [10]. Hence, p_i (in the case of uniform probability distribution function) can be formulated as:

$$p_i = \left(\frac{\text{Common range}}{\text{System range}}\right) \quad (3)$$

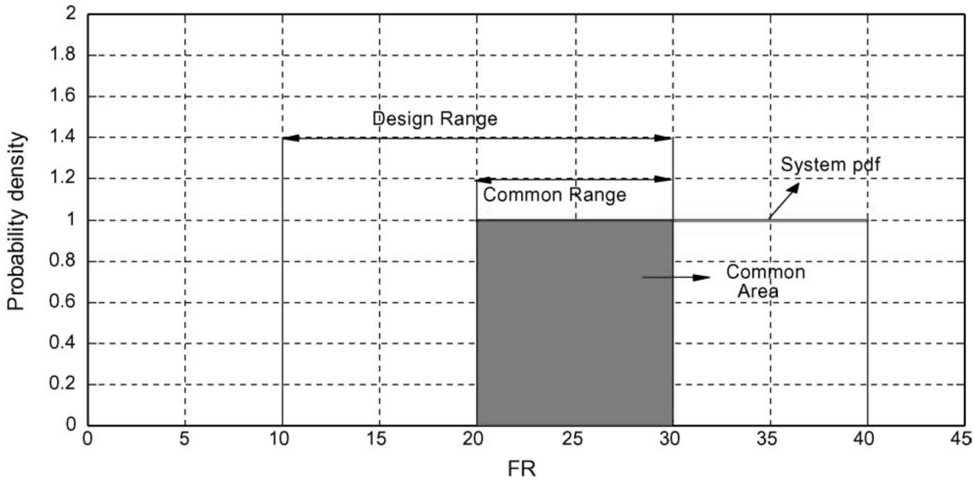

Fig. 2 Design range, system range, common range and probability density function of a FR [10]

The abovementioned crisp AD approach is suitable for solving decision-making problems under certainty. However, one needs to be aware that expressing decision variables in the form of crisp numbers would be ill defined [12]. While crisp AD approach cannot be utilized when available information is qualitative and linguistic, fuzzy set theory is particularly useful when dealing with imprecision of language and human thought in decision-making process [13].

As for fuzzy information axiom approach, triangular fuzzy number (TFN, as shown in Fig. 3) can be used to express data in linguistic terms when system and design ranges happen to be stated linguistically. The notation of TFN and information content are formulated by Eq. 4 and Eq. 5 respectively. In this case, the common area is the intersection between TFNs of design range and system range as illustrated in Fig. 4 [14].

$$\mu(x) = \left\{ \begin{array}{ll} \frac{x - c}{a - c}, & c \leq x \leq a \\ \frac{b - x}{b - a}, & a \leq x \leq b \\ 0, & \text{otherwise} \end{array} \right\} \quad (4)$$

$$I_i = \log_2\left(\frac{\text{TFN of system range}}{\text{Common area}}\right) \quad (5)$$

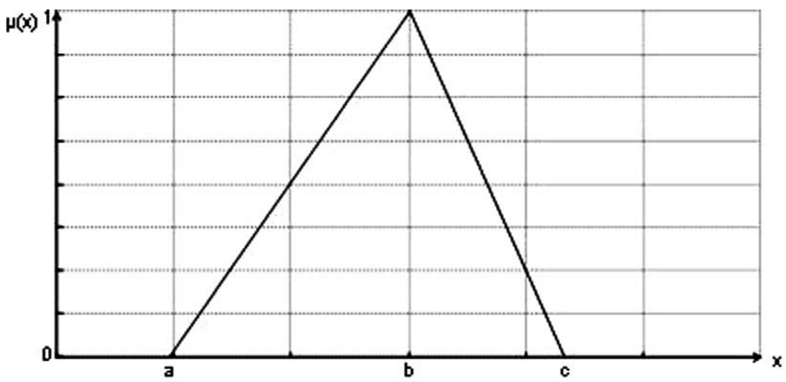

Fig. 3 Triangular fuzzy number [13]

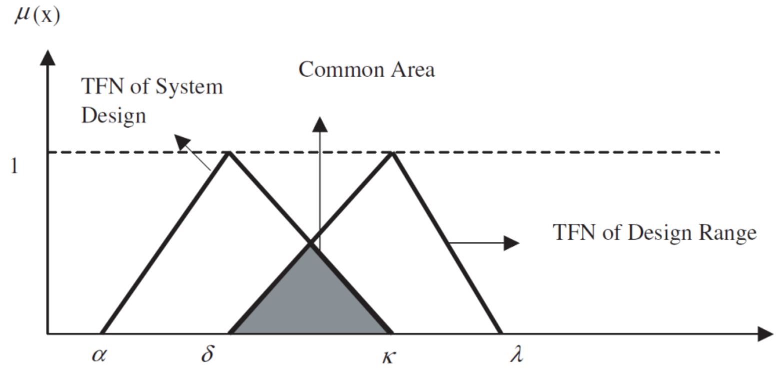

Fig. 4 The common area of system and design ranges [14]

Both crisp and fuzzy AD approaches have been applied extensively for design and decision-making purposes. A review of literature indicates that AD principles have been utilized in five major areas of applications namely (1) product design, (2) system design, (3) manufacturing system design, (4) software design and (5) decision-making [13]. For instance, Shin et al. [15] employed the crisp approach in designing a nuclear fuel spacer grid. Apart from that, Gumus et al. [16] developed a product development lifecycle model based on the independence axiom and design domains. As for fuzzy AD, the approach is utilized in a multi-attribute transportation company selection problem by Kulak and Kahraman [14]. Also, it has been used in manufacturing system selection by Kulak et al. [12]. The authors applied fuzzy AD approach to identify suitable punching machine among a number of alternatives. Besides that, Celik et al. [17] also employed the information axiom to select the best docking facilities of shipyards. Nonetheless, the application of AD principles for sustainable manufacturing system can be considered being in its infancy stage.

3. Optimization methodology: the design equation

The optimization problem of sustainable manufacturing involves parameters (according to categories, together with desired levels) as shown in Table 2 [7]. To provide a simpler visualization on the cause-effect relationship, the mathematical model can be derived into the following FRs to be satisfied by an optimized manufacturing system in general and a set of DPs as the corresponding solutions to fulfil the FRs:

FR_1: To maintain cutting condition within manageable range
FR_2: To attain satisfactory machining performance
FR_3: To achieve process sustainability at desired level

DP_1: Parameters of cutting condition must be set within constraints
DP_2: Employ adequate cooling method
DP_3: All sustainability factors to satisfy respective requirement

The relationship between the FRs and DPs can be stated in terms of design equation (see Eq. 6). Note that both DP_1 and DP_2 have to be considered in order to achieve FR_2. Previous research has proven that machining performance (e.g., surface roughness and material removal rate) differs with cooling methods and cutting conditions utilized for the machining process [3, 7]. Besides that, it can be seen that all three DPs are involved when it comes to satisfying FR_3. This is due to the dependency of sustainability parameters on cutting condition and cooling method set by the user as experiments have shown that machining cost and energy consumption vary with cutting speed and coolant delivery systems [3]. In this case, the design matrix obtained is a triangular matrix which signifies that the design being considered is a decoupled design. Under this circumstance, with the purpose of satisfying the independence axiom, DPs should be adjusted in a particular sequence. DP_1 should be varied first to meet FR_1, followed by adjusting DP_2 to fulfil

FR_2. Lastly, DP_3 can be determined to achieve FR_3 [10]. In other words, parameters of cutting condition such as cutting speed and feed rate must first be decided before proceeding to select cooling method to fulfil required machining performance. Finally, for each selected cooling method (with given cutting conditions), sustainability parameters can be analyzed and compared against the requirement.

$$\begin{bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_2 \\ \mathrm{FR}_3 \end{bmatrix} = \begin{bmatrix} \mathrm{X} & 0 & 0 \\ \mathrm{X} & \mathrm{X} & 0 \\ \mathrm{X} & \mathrm{X} & \mathrm{X} \end{bmatrix} \begin{bmatrix} \mathrm{DP}_1 \\ \mathrm{DP}_2 \\ \mathrm{DP}_3 \end{bmatrix} \tag{6}$$

Table 2 Parameters involved in optimization problem

Category	Parameter	Desired level
Cutting condition	Cutting speed (V)	$V_{min} \leq V \leq V_{max}$
	Feed rate (f)	$f_{min} \leq f \leq f_{max}$
	Depth of cut (d)	$d_{min} \leq d \leq d_{max}$
Sustainability	Machining cost (MC)	$\mathrm{MC} \leq \mathrm{MC}'$
	Energy consumption (EC)	$\mathrm{EC} \leq \mathrm{EC}'$
	Waste reduction (WR)	$\mathrm{WR} \geq \mathrm{WR}'$
	Personnel health (PH)	$\mathrm{PH} \geq \mathrm{PH}'$
	Operational safety (OS)	$\mathrm{OS} \geq \mathrm{OS}'$
	Environmental friendliness (EF)	$\mathrm{EF} \geq \mathrm{EF}'$
Functional/Performance	Surface roughness (R_a)	$R_a \leq R_a'$
	Cutting force (F)	$F \leq F'$
	Tool life (T)	$T \geq T'$
	Material removal rate (M_R)	$M_R \geq M_R'$
	Chip breakability (CB)	$\mathrm{CB} \geq \mathrm{CB}'$

4. Case study

In this section, a case study is presented to demonstrate the application of AD principles for the purpose of optimizing the process sustainability. The three alternative processes to be considered in this study are namely (1) conventional machining, (2) high pressure jet assisted machining (HPJAM) and (3) cryogenic machining (cryo). Knowing that the use of cooling/lubrication fluid (CLF) is the main factor that impacts the environment and sustainability, HPJAM and cryogenic machining are considered as alternatives to conventional flood machining in this study due to their innovative methods of reducing/eliminating the consumption of CLF [1, 9].

HPJAM exhibits an innovative way of cooling and/or lubricating the cutting zone by having an extremely high-pressure CLF delivery system at a relatively lower flow rate. This enables a comparatively small amount of CLF to penetrate closer to the share zone (region which undergoes highest temperature during machining) and cools it [9]. Earlier research has proven that HPJAM can provide a more sustainable process and improve machining performance in terms of chip breakability and material removal rate [18, 19].

Cryogenic machining is another innovative manner of cooling the cutting tool and/or part during machining. Instead of oil-based CLF, it delivers a cryogenic CLF to the cutting region. Usually, liquid nitrogen is used as coolant in this process. The fluid eventually evaporates and returns to the atmosphere. This eliminates the need to clean part, chips and machine tool, and thus leads to lower disposal cost [9]. Other than that, cryogenic machining is able to bring better part surface quality, increased material removal rate and hence higher productivity [4].

Recently, experiments have been conducted to evaluate the sustainability performance of the abovementioned processes by using 100 mm centerless-ground Inconel 718 round bars with a diameter of 40 mm as work piece [3]. To show a more realistic application, empirical data collected from the experiments are adopted in this study and will be used in subsequent sections.

4.1 Determining the cutting condition

In this study, machining parameters employed are presented in Table 3. These parameters were chosen according to previously published research work on cryogenic machining and HPJAM [20-22]. For more detailed setup of experiments (such as tool type and CLF flow rate), readers are directed to earlier research work [3].

Table 3 Cutting condition being considered

Parameter	Value
Cutting speed, V [m/min]	30, 60
Feed rate, f [mm]	0.25
Depth of cut, d [mm]	1.2

4.2 Selection of adequate cooling method

Cooling method can be selected from a series of available processes in order to achieve necessary machining performance (FR_2). For instance, by using cryogenic machining, the surface roughness of the produced part can be enhanced as compared to conventional machining [4]. This study assumes that all three processes (conventional machining, HPJAM and cryogenic machining) are capable of meeting the required machining performance with cutting conditions given in the last section and shall proceed for further analysis.

4.3 Comparison of sustainability performance against desired level

As mentioned in earlier section, FR_3 dictates the requirement to achieve process sustainability at desired level. This FR can be further decomposed to specify requirement for each of the sustainability factors. An example of decomposed FR_3 is shown as follows:

$FR_{31,MC}$: Machining cost per part must be in the range of 0 to 1.85 €.
$FR_{32,EC}$: Energy consumption per part must be in the range of 0 to 0.15 kWh.
$FR_{33,WR}$: Part cleaning cost must be in the range of 0 to 0.08 €.
$FR_{34,EF}$: Environmental friendliness must be at least 5 (5,20,20).
$FR_{35,OS}$: Operational safety must be at least 5 (5,20,20).
$FR_{36,PH}$: Personnel health must be at least 5 (5,20,20).

The selection of cutting condition with cutting speed of 30 m/min, feed rate of 0.25 mm, and depth of cut of 1.2 mm yields the corresponding machining costs (include cutting tool and CLF costs), energy consumption rate and waste processing cost as shown in Table 4 [3]. Table 4 also shows sustainability performances such as environmental friendliness and personnel health which are graded qualitatively. The information axiom can be used to construct a hybrid model that facilitates the analysis of sustainability performance.

For operational sustainability factors (S_{OP}) such as machining costs, energy consumption and waste management cost, crisp AD approach can be used to translate the evaluation results into performance scores in terms of information content using Eq. 2 and Eq. 3. From Table 4, it can be seen that the evaluation results for quantitative factors are given in individual values instead of a range that consists of upper and lower limits. This makes calculation of common range impossible as system range is not provided. To overcome this difficulty, an acceptance threshold can be introduced. It can be deemed as maximum allowable variation for each parameter and serves as an imaginary upper limit for each system range. An illustrative example is given in Fig. 5 to show the computation of common range for machining costs of HPJAM. In the figure, the intersection between design range and system range is crosshatched. Note that the upper limit of system range is obtained by introducing a 20 % variation in machining costs. Detailed computation of information content for machining costs of HPJAM is presented as follows:

Area of system range is: $[(1.794 + 0.2 \times 1.794) - 1.794] \times 1 = 0.3588$

Area of common range is: $(1.850 - 1.794) \times 1 = 0.056$

$$I_i = \log_2\left(\frac{\text{System range}}{\text{Common range}}\right) = \log_2\left(\frac{0.3588}{0.056}\right) = 2.6797$$

Table 4 Sustainability performance corresponding to cutting condition of V = 30 m/min, d = 1.2 mm, and f = 0.25 mm

Machining process	Machining costs (€/part)	Energy consumption (kWh/part)	Waste management (€/part)	Environmental friendliness	Operational safety	Personnel health
Conventional machining	1.811	0.148	0.078	Poor	Poor	Poor
Cryogenic machining	2.016	0.147	0.004	Excellent	Excellent	Excellent
HPJAM	1.794	0.202	0.074	Fair	Good	Good

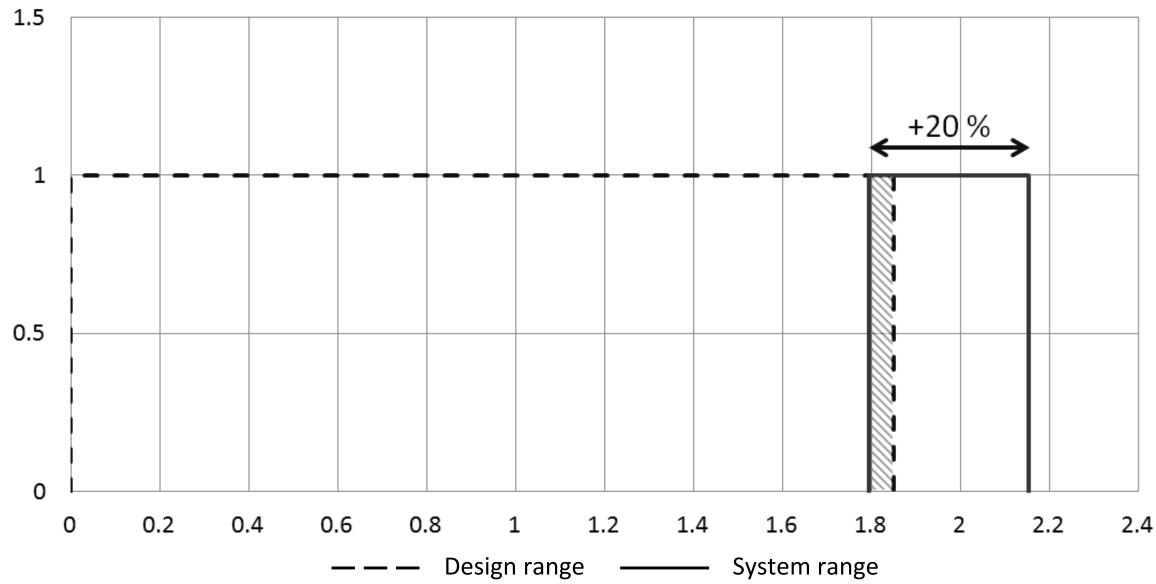

Fig. 5 Machining costs of HPJAM: intersection of design range and system range

Fuzzy AD approach has been applied extensively when dealing with linguistic terms. In this scenario, it is particularly helpful for analyzing sustainability performance for environmental friendliness, personnel health and operational safety (S_{SHE}) by converting qualitative terms like "poor", "fair" and "good" into information content. As shown in Fig. 6, the stakeholder subjectively evaluates the alternatives with the linguistic term "poor" if these criteria are assigned a score of (0, 0, 6) over 20; "fair" with a score of (4, 7, 10) over 20; "good" with a score of (8, 11, 14) over 20; "very good" with a score of (12, 15, 18) over 20; "excellent" with a score of (16, 20, 20) over 20 [14]. With the design and system ranges determined, Eq. 4 and Eq. 5 can be applied to compute the information content for each FR in each alternative. With the aid of Fig. 7, a detailed calculation of information content for environmental friendliness of HPJAM is given as follows:

Area of system range is: 0.5 × (10 – 4) × 1 = 3

Area of common range is: 0.5 × (10 – 5) × 0.2778 = 0.6945

$$I_i = \log_2\left(\frac{\text{System range}}{\text{Common range}}\right) = \log_2\left(\frac{3}{0.6945}\right) = 2.111$$

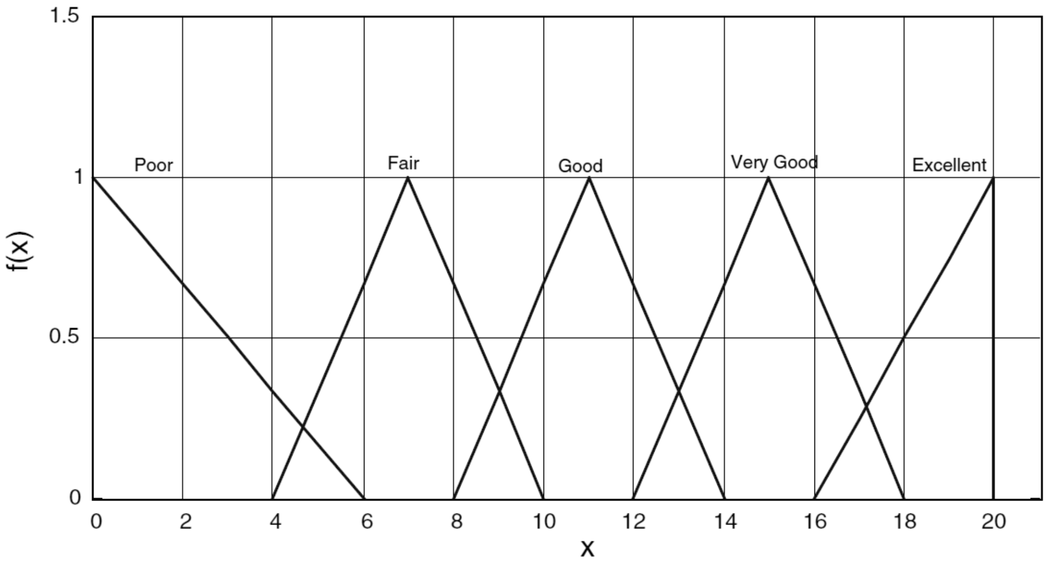

Fig. 6 TFNs for intangible factors [14]

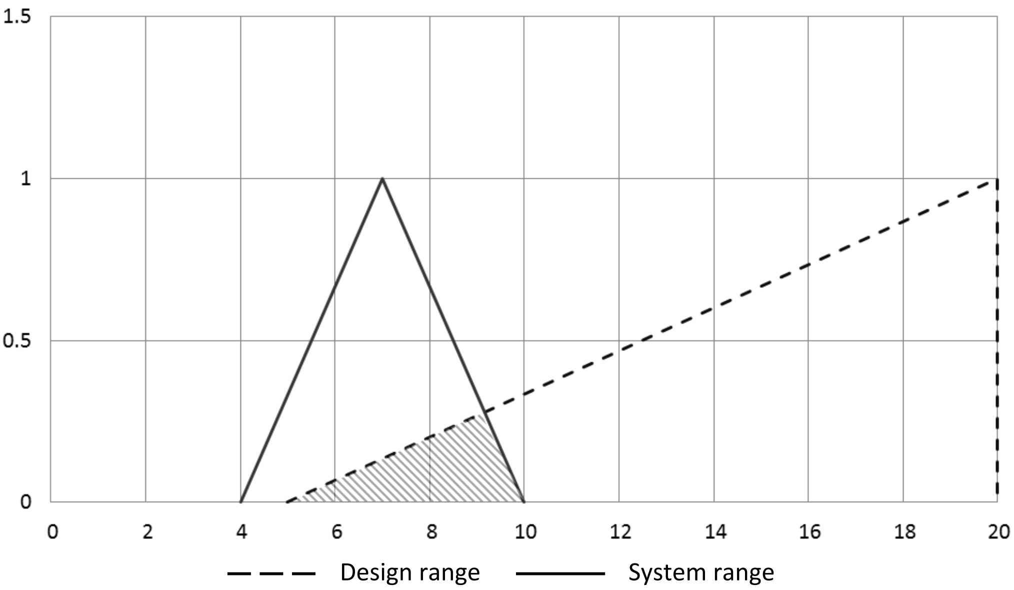

Fig. 7 Environmental friendliness of HPJAM: crosshatched area denotes intersection of design range and system range

Information content for each alternative machining process is tabulated in Table 5 according to respective sustainability factors. One should be aware that these calculated values are not subjected to criteria weight. Respective weighting factors can be imposed on S_{SHE} and S_{OP} [2] and it can be done by applying Eq. 7 to the values tabulated in Table 5. I_{ij} denotes information content of the alternative i for the criterion j; w_j represents the weight of the criterion j; p_{ij} symbolizes the probability of achieving the functional requirement FR_j (criterion j) for the alternative i [14]. In this case, criteria weight of 0.5 is used for both S_{SHE} and S_{OP}. As a result, weighted information contents are obtained as shown in Table 6. After that, unit index of each category are calculated by dividing the total information contents in Table 6 by the number of sub-criteria of category. For instance, the category of operational sustainability factor has three sub-criteria namely machining costs, energy consumption and waste management. The total information content for these factors should be divided by three in order to obtain the unit index for operational sustainability. This step is essential because each criterion consists of different numbers of sub-criteria which may affect the sum of information content [12]. Calculated unit indexes are organized and shown in Table 7. Table 7 indicates that conventional machining is the only viable process that satisfies all required sustainability performance. Both cryogenic machining and HPJAM have infinite information content due to unsatisfying machining costs and energy consumption respectively.

$$I_{ij} = \begin{Bmatrix} \left[\log_2\left(\frac{1}{p_{ij}}\right)\right]^{1/w_j}, & 0 \leq I_{ij} < 1 \\ \left[\log_2\left(\frac{1}{p_{ij}}\right)\right]^{w_j}, & I_{ij} > 1 \\ w_j\,, & I_{ij} = 1 \end{Bmatrix} \tag{7}$$

Table 5 Unweighted information contents

Machining process	Machining costs	Energy consumption	Waste management	Environmental friendliness	Operational safety	Personnel health
Conventional machining	3.2152	3.8875	2.9635	6.9773	6.9773	6.9773
Cryogenic machining	Infinite	3.2928	0.0000	0.0000	0.0000	0.0000
HPJAM	2.6797	Infinite	1.3026	2.1110	0.6781	0.6781

Table 6 Weighted information contents

Machining process	Machining costs	Energy consumption	Waste management	Environmental friendliness	Operational safety	Personnel health
Conventional machining	1.7931	1.9717	1.7215	2.6415	2.6415	2.6415
Cryogenic machining	Infinite	1.8146	0.0000	0.0000	0.0000	0.0000
HPJAM	1.6370	Infinite	1.1413	1.4529	0.4598	0.4598

In the event when analysis results show infinite unit index for all processes, the procedure mentioned in sections 4.1 and 4.2 should be repeated to alter the parameters. As an example, cutting speed can be altered from 30 m/min to 60 m/min which in turn varies the machining costs and energy consumption (with other machining parameters unchanged and corresponding machining performance unaffected).

Table 7 Unit indexes for weighted information content (* denotes viable process that satisfies all FRs with minimum information content)

Manufacturing process	Operational sustainability	Safety, health and environment	Sum
Conventional machining	1.8288	2.6415	4.4702*
Cryogenic machining	Infinite	0.0000	Infinite
HPJAM	Infinite	0.7909	Infinite

Table 8 shows the revised sustainability performance when cutting speed of 60 m/min is used. This set of sustainability performances can eventually be converted to unit indexes when procedure stated in section 4.3 is repeated (see Table 9). It can be seen that both cryogenic machining and HPJAM are viable processes as they fulfil the required sustainability performance. Nevertheless, cryogenic machining should be selected since it has the smallest information content.

Table 8 Sustainability performance corresponding to cutting condition of V = 60 m/min, d = 1.2 mm, and f = 0.25 mm

Machining process	Machining costs (€/part)	Energy consumption (kWh/part)	Waste management (€/part)	Environmental friendliness	Operational safety	Personnel health
Conventional machining	2.049	0.082	0.078	Poor	Poor	Poor
Cryogenic machining	1.461	0.077	0.004	Excellent	Excellent	Excellent
HPJAM	1.319	0.105	0.074	Fair	Good	Good

Table 9 Unit indexes for weighted information content (* denotes viable process that satisfies all FRs with minimum information content)

Manufacturing process	Operational sustainability	Safety, health and environment	Sum
Conventional machining	Infinite	2.6415	Infinite
Cryogenic machining	0.0000	0.0000	0.0000*
HPJAM	0.3804	0.7909	1.1713

5. Discussion

Based on empirical data, when the cutting speed is set at 30 m/min, both cryogenic machining and HPJAM are being ruled out because of excessive machining costs and energy consumption respectively. Eventually, conventional machining is the remaining process to be selected as optimized manufacturing process. This is clearly indicated in Table 6 as information contents for machining costs of cryogenic machining and energy consumption of HPJAM show infinite values. Subsequently it leads to infinite unit indexes for both the processes as shown in Table 7 and conventional machining (having the smallest sum of unit indexes) is preferred as optimized process. When the cutting condition is altered, the optimization procedure is iterated and a new set of information content and unit indexes is yielded. In contrast, machining costs of conventional machining is too costly when higher cutting speed is used, causing the process to be excluded. As tabulated in Table 9, both cryogenic machining and HPJAM are acceptable but according to the information axiom, cryogenic machining should be the optimized process since it carries the smallest sum of unit indexes. The approach presented in Section 4 is able to point out the most viable process with the consideration of sustainability performances. After that, decision-maker can either decide to accept the sustainability level of the selected process or iterate the optimization procedure by adjusting the cutting condition and/or reselecting cooling method to obtain improved sustainability performance. As demonstrated in Section 4, adjustment in cutting condition may lead to changes in operational sustainability and thus a different outcome in terms of viable processes.

One should notice that criteria weights used in Section 4 are equally set as 0.5 for both S_{SHE} and S_{OP}. In this case, setting different weight factors for the criteria does not affect the outcome significantly. For instance, if the weight factors are set as 0.2 for S_{SHE} and 0.8 for S_{OP} (V = 60 m/min), the calculated unit indexes will be as shown in Table 10.

The result is unchanged as compared to the previous configuration that uses equal weight factors as cryogenic machining is still having the smallest total unit indexes. The performance of cryogenic machining in terms of S_{SHE} is simply overwhelming comparatively to other processes. Nevertheless, criteria weight can potentially be a helpful feature when a bigger number of competitive processes are being considered.

Table 10 Unit indexes for weighted information content, with adjusted criteria weight (* denotes viable process that satisfies all FRs with minimum information content)

Manufacturing process	Operational sustainability	Safety, health and environment	Sum
Conventional machining	Infinite	1.4748	Infinite
Cryogenic machining	0.0000	0.0000	0.0000*
HPJAM	0.4118	0.4826	0.8945

Acceptance threshold of 20 % is used throughout the analysis of S_{OP} in Section 4.3. This value signifies variation in sustainability performance that a decision-maker/stakeholder can allow and may be adjusted to other value should the stakeholder deems appropriate (e.g., 50 %). To understand the effect of altering the acceptance threshold, calculation of information content for machining costs of HPJAM is repeated as follows:

Area of system range is: $[(1.794 + 0.5 \times 1.794) - 1.794] \times 1 = 0.8970$

Area of common range is: $(1.850 - 1.794) \times 1 = 0.056$

$$I_i = \log_2\left(\frac{\text{System range}}{\text{Common range}}\right) = \log_2\left(\frac{0.8970}{0.056}\right) = 4.0016$$

It can be seen that the newly calculated information content differs from the previous value of 2.6797. When the value of acceptance threshold is increased, the system range widens accordingly, leading to a smaller possibility of satisfying the requirement of machining costs and thus an increased value of information content. Therefore, it is plausible to have individual acceptance threshold values for each of the sustainability performance under S_{OP} category. For example, decision-maker/stakeholder may decide that a 50 % variation is allowed for machining costs but the variation in energy consumption must not exceed 20 %. This may imply the stringency of a decision-maker/stakeholder in controlling the variation of a certain performance in the long run.

6. Conclusion

To gain economic advantage and enhanced environmental performance, sustainability principles have to be integrated into machining processes. One of the engineering challenges is to attain an optimized solution which involves combinations of minimum and maximum levels achievable within the constraints imposed. From the design equation presented in Section 3, a step-wise approach is proposed with the help of AD principles. A case study that involves three alternative processes is presented to demonstrate the application of the proposed approach and it can be concluded that an optimized manufacturing solution can be obtained by following a step-by-step procedure namely (1) setting the cutting condition, (2) selecting adequate cooling method and (3) analysis of sustainability performance. Subsequently, analysis results may be reviewed and accepted if desired level of sustainability is attained. Should the product require enhanced sustainability, the optimization procedure can be iterated to achieve satisfying performance.

The case study also includes a hybrid model (consists of crisp and fuzzy AD approaches) that facilitates analysis of sustainability performance. The proposed model is able to point out the most viable machining process (that satisfies all sustainability FRs) by using weighted information content as indication. For example, conventional machining has been identified as the most viable/sustainable machining process when cutting speed is set as 30 m/min. However, in the case where the cutting speed is altered to 60 m/min (with other cutting parameters unchanged), cryogenic machining is in turn indicated as the most sustainable machining process. The ability of the proposed approach in discriminating incompetent processes based on empirical data (in the aspect of sustainability) is expected to benefit product development and manufacturing companies in practicing environmentally conscious manufacturing as part of sustainable product realization. Potentially, it can facilitate decision-making process from a sustainable manufacturing standpoint and thus lead to a greener and cleaner production as well as an enhanced environmental policy for the company. Criteria weight does not affect the outcome of the analysis to a significant extent but it may be a useful feature if a greater amount of comparable processes are involved in the study. The effect of acceptance threshold (allowable variation in S_{OP} performance) is also discussed. Having separate acceptance threshold value for each of the criteria under the category of S_{OP} is possible and these individual values suggest the stringency of decision-maker/stakeholder in managing the variation of certain operational performance.

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