ISSN 1854-6250

APEM journal

Advances in Production Engineering & Management

Volume 11 | Number 3 | September 2016

University of Maribor
Published by PEI
apem-journal.org

Advances in Production Engineering & Management

Identification Statement

ISSN 1854-6250 | Abbreviated key title: **Adv produc engineer manag** | Start year: 2006
ISSN 1855-6531 (on-line)

Published quarterly by **Production Engineering Institute (PEI)**, **University of Maribor**
Smetanova ulica 17, SI – 2000 Maribor, Slovenia, European Union (EU)

Phone: 00386 2 2207522, Fax: 00386 2 2207990
Language of text: English

APEM homepage: apem-journal.org
University homepage: www.um.si

APEM Editorial

Subscription Rate: 120 EUR for 4 issues (worldwide postage included); 30 EUR for single copies (plus 10 EUR for postage); for details about payment please contact: info@apem-journal.org
Cover and interior design: Miran Brezocnik
Printed: Tiskarna Koštomaj, Celje, Slovenia
Subsidizer: The journal is subsidized by Slovenian Research Agency

Advances in Production Engineering & Management is indexed and abstracted in the **WEB OF SCIENCE** (maintained by **THOMSON REUTERS**): **Science Citation Index Expanded**, **Journal Citation Reports** – Science Edition, **Current Contents** – Engineering, Computing and Technology • **Scopus** (maintained by **Elsevier**) • **Inspec** • **EBSCO**: Academic Search Alumni Edition, Academic Search Complete, Academic Search Elite, Academic Search Premier, Engineering Source, Sales & Marketing Source, TOC Premier • **ProQuest**: CSA Engineering Research Database – Cambridge Scientific Abstracts, Materials Business File, Materials Research Database, Mechanical & Transportation Engineering Abstracts, ProQuest SciTech Collection • **TEMA** (**DOMA**) • The journal is listed in **Ulrich's** Periodicals Directory and **Cabell's** Directory

University of Maribor
Production Engineering Institute (PEI)

Advances in Production Engineering & Management

Volume 11 | Number 3 | September 2016 | pp 155–254

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Journal homepage: apem-journal.org

ISSN 1854-6250 (print)
ISSN 1855-6531 (on-line)

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Advances in Production Engineering & Management
Volume 11 | Number 3 | September 2016 | pp 159–172
http://dx.doi.org/10.14743/apem2016.3.217
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Production monitoring system for understanding product robustness

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A B S T R A C T

In the current quality paradigm, the performance of a product is kept within specification by ensuring that its parts are within specification. Product performance is then validated after final assembly. However, this does not control how robust the product performance is, i.e. how much it will vary between the specification limits. In this paper, a model for predicting product performance is proposed, taking into account design, assembly and process parameters live from production. This empowers production to maintain final product performance, instead of part quality. The PRECI-IN case study is used to demonstrate how the monitoring system can be used to efficiently guide corrective action to improve product performance. It is claimed that the monitoring system can be used to dramatically cut the time taken to identify, plan and execute corrective action related to typical quality issues. To substantiate this claim, two further cases comparable to PRECI-IN, in terms of complexity, material and manufacturing process, were taken from different industries. The interviews with quality experts revealed that the typical time taken for corrective action for both cases was accounted to be seven days. Using the monitoring system for the PRECI-IN case, similar corrective action would have been achieved almost immediately.

A R T I C L E   I N F O

Keywords:
Product robustness
Performance variation
Robustness monitoring system
Performance consistency
Unit to unit robustness

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Article history:
Received 27 May 2016
Revised 5 August 2016
Accepted 17 August 2016

1. Introduction

1.1 General

A robust product has consistent performance, showing little variation from one unit to the next. The variation in functional performance is determined by both design and production [1], as described by the Variation Management Framework (VMF) [2]. Several researchers have explained how to handle robustness during design [3-5]. Performance variation is driven by its sensitivity to design parameters and how much they vary. Many tools are available to help design engineers to manage design parameter variation and design sensitivity [6]. However, few methods have been developed to achieve robustness from a manufacturing perspective which currently has the focus on producing part to a specification determined by design. Quality estimations, monitoring and control in industry are driven by Statistical Quality Control (SQC) and Statistical Process Control (SPC) [7]. Common practice is to understand process variables through SPC techniques and change their process settings for reducing product variation. This is to much an extent reactive control of performances and the estimation accuracies are limited due to limited sampling. Technology enhancement with a high degree of automation, allowing 100 % in-line inspection, can improve the control of final product variation [8]. However these quality systems work on the principle of controlling the variables, not adjusting one to compensate another. Also performance estimations are of larger volumes can't currently be used to estimate the performance of a specific unit running on the line.

The current state of the art performance prediction can be exemplified by the Artificial Neural Network Performance prediction model [9], which suggests that batches of parts be produced and measured before assembly to allow for matching complementary variations in parts for better performance. Neural network principles are effectively applied in process manufacturing industries to estimate the final product performance with measured variables beginning of the cycle [10]. This method also considers the variables relationship. However this system is proactive to only assembly, not for manufacturing. Also does not address products with multiple functions and parameters interlinked.

This research focuses on method of reducing unit to unit product variation during mass production by complimenting variables with their relationships for each unit. This means that if all units of the product were to be functionally tested after production, there would be less variation between the performances of each unit. However the paper does not address the change in performance of a product through its life, or in different use condition/scenarios. Unit to unit performance variation of a product is the result of variations in its parts and processes. Fig. 1 shows the representation of variation inflow to the typical production process.

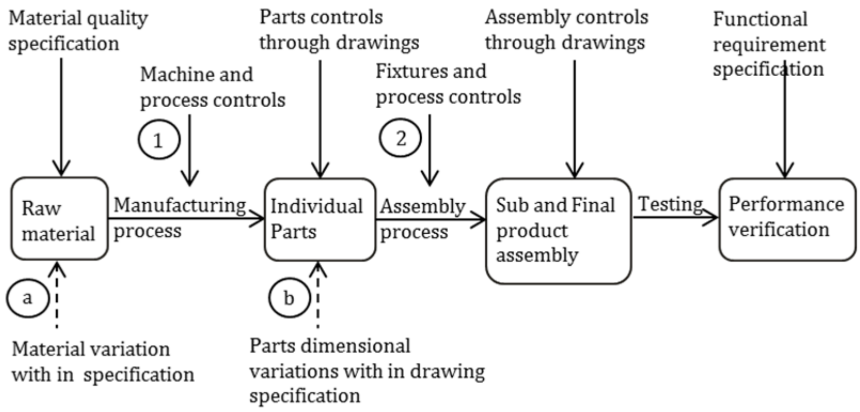

Fig. 1 A schematic representation of the production process with controls and variations

The research approach is to create a robustness monitoring system for production, which allows for understanding the incoming variation "a" and "b" (Fig. 1) and opportunities to compensate for them through "1" and "2" (Fig. 1). To create a model connecting the end product performance with all of the influencing variables, one needs to extract the relationships throughout, which are derived during product design and production tools development.

1.2 Parameter sensitivity

Variations of the part dimensions influence different product functions. Their degree of influence is known as sensitivity and can be non-linear and therefore dependent on nominal value. Sensitivity plays an important role while improving the parts and their design parameters in production to achieve consistency in final product performance.

1.3 Parameter interactions

It is not always the case that parameters influence product functions independently. Situations are present when the influence of a design parameter changes due to variations in the other design parameter. These interactions add more complexity when it comes to mapping influences of relationships in a design. However, good news is that the interaction effects are not as common as first order interactions and they also tend to have less influence than the first order interactions [11].

1.4 Axiomatic design

Complexity increases when each design parameter influences more than one function. For the design of a snap hook, the thickness of snap hook arm has an influence on the force required to deflect the arm and also the tensile strength of the hook once the snap has engaged. If we need to increase the tensile strength of the snap increasing the arm thickness will help but will create greater resistance to deflection.

1.5 Assembly process parameters

Assembly strategy gets defined along with product geometry concept. Variables in assembly can be dimensions of the parts and also fixtures in use [12, 13]. Sometimes even sub processes, like amount of glue applied, torque applied, etc. can be assembly variables. When these variables connect to product performance, applying them to compensate for parts variations is an opportunity in assembly to achieve performance constancy.

1.6 Manufacturing process parameters

The manufacturing process used for part production generates variation in part's dimensions. An injection moulding process relies on, pressure, temperature and cooling time, etc. as process parameters; similarly a machining process relies on speed, feed, tool size etc. as process variables. Those can be applied to generate the parts as needed. For example, in an outsourced part is made produced where the measurement report shows the batch to be close to the upper specification limit, a corresponding in-house part can be made closure to the lower specification limit to compensate.

The basic principle of this approach is "as we cannot eliminate the variations, apply them in order to compensate one another, nullify their effect on the final product". The monitoring system developed in this article allows this approach to be done more effectively.

2. Method for building robustness monitoring system

Engineering design philosophy builds the relationship of each design parameter to the final product functional requirements. Eq. 1, and Eq. 2 shows the simplest form of a product functional requirement and its variation, in which DP refers to Design Parameter and *s* refers to the Sensitivity of the function to variation of that DP.

$$\mathrm{Fn} = (s1 \times DP1) + (s1 \times DP2) + .. + (s\mathrm{n} \times DPn) \tag{1}$$

$$\Delta\mathrm{Fn} = (s1 \times \Delta DP1) + (s1 \times \Delta DP2) + .. + (s\mathrm{n} \times \Delta DPn) \tag{2}$$

DP variations (ΔDP) are caused by various process and equipment influences in manufacturing. Identifying all those Influencing Factors (IF) and quantifying the DP sensitivity to each of them is required to establish the link between variations in functional requirement to variations in manufacturing. The nature of the IFs derives the monitoring system requirements. The method followed to establish the monitoring system is shown in Fig. 2.

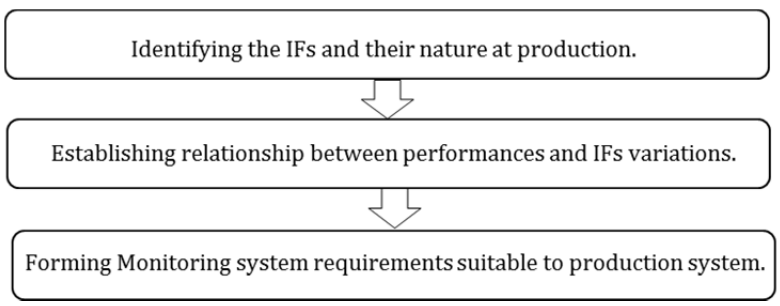

Fig. 2 Steps followed to establish monitoring system content and structure

2.1 Identifying IFs and their nature

Different influencing factors cause variations at various stages of production shown in the Fig. 3. The nature of all the IFs is not the same and production's ability to apply change differs. Compensating one IF by controlling another, is dependent on many aspects as outlined here:

Time: In the chain of production activities, the first generated variation becomes the base for later IF to be adjusted accordingly. Certain outsourced parts arrive at the assembly warehouse before may constitute the first IF.

Changeability: Certain influencers are rigid in nature. For example, a dimension in plastic mould is made 15 microns bigger is well within the machining tolerance, and cannot be changed in production.

Agility: How quick production can act on IF also differs. Changing a tightening torque is quick, and may take only a few seconds but mould temperature change takes an hour to stabilize. This limit's the application while choosing the IF for compensation.

Axiomatic conditions: When IFs affect the performance of multiple functions of the product, it becomes more complex to manage. Adjusting one IF to compensate for another, may bring the performance of one function back to the target value, but may have negative effects on other functions.

Degree of Control: All IFs will not completely be within production control. For example, raw material characteristics are specified with certain variation acceptance. As long as it is maintained within the range, material batches are quality passed, and cannot be asked to change. These are semi controlled. Ambient temperature and humidity etc. are often uncontrolled. However, both semi-controlled and uncontrolled can be measured and compensated by other controlled IFs.

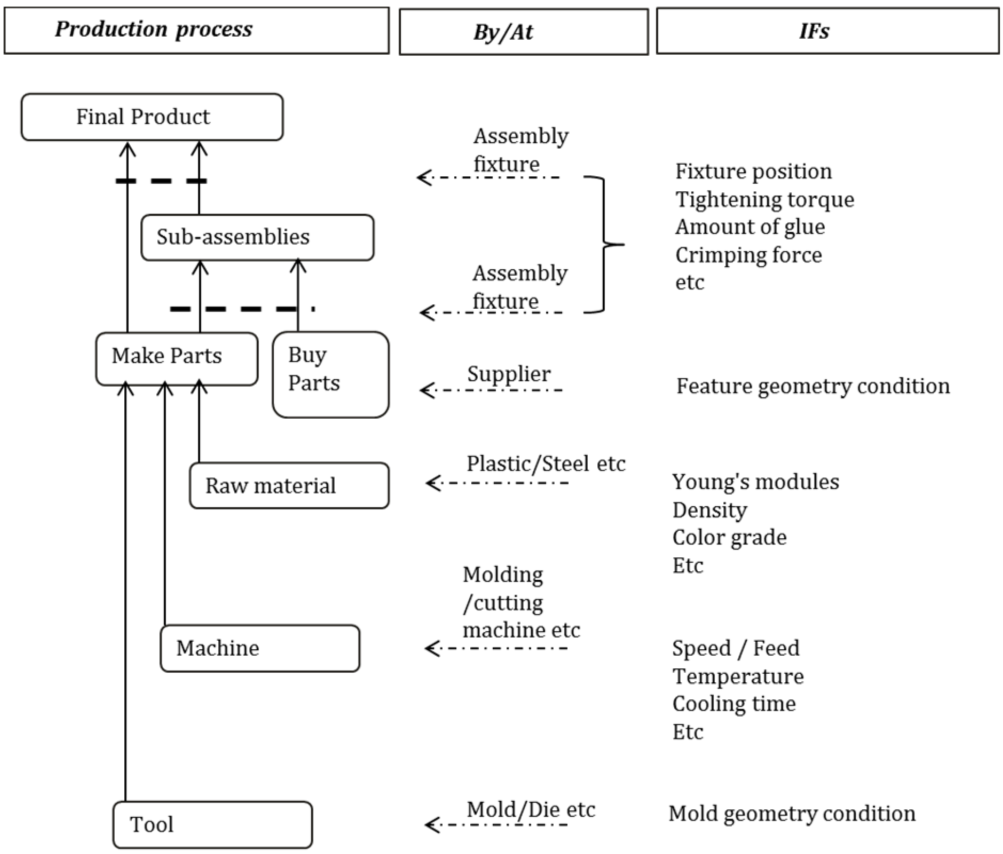

Fig. 3 Mapping of IFs over production process

2.2 Establishing relationships

Design Parameters (DPs) are identified at product design. Relationship equations of these design parameters to the Functional Requirements (FRs) are determined by the designed concept. Many products designs choose final assembly dimensions as targets to achieve FRs, e.g. spring compression length in final assembly is maintained in production to achieve push force function. These Dimensional Targets (DT) build with DPs to achieve FRs indirectly. Some cases DT itself can be FR, e.g. product length, flushness, gap uniformity, etc. Many assembly processes involve the use of fixtures to achieve DTs. In this case the dimensions of the fixture would be an assembly parameter (AP) which also influences on the FRs. However the relationship of manufacturing Process Parameters (PPs) to DPs is generated through the tools design (moulds, dies, fixtures, etc.)[14-16]. Fig. 4 shows the production process with variables identification. Here all APs and PPs are IFs.

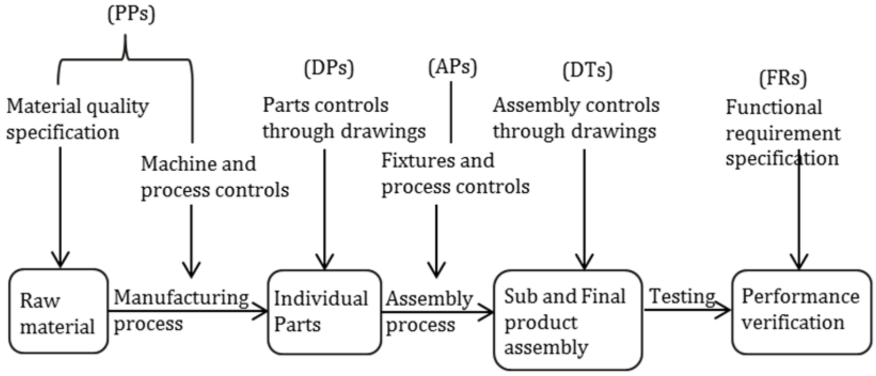

Fig. 4 Variables in discussion identified on production process

2.3 Monitoring system requirement

The intention of the monitoring system is to indicate which function is varying, by how much and due to which IFs. After identification, the relationship between those IFs and the function requirement helps in determine by how much they need to be adjusted to improve intended function.

Generic quality focused production approaches aim to maintain parts and assemblies as per drawing specifications. This ensures the functional requirements to achieve within specification. When unit to unit product robustness is in focus, FRs not only needs to be within specification, but they also need to be consistent from unit to unit. Product robustness as defined by John P King [17] is "*A system that is more ROBUST is less sensitive to the sources of variability in its performance*". To understand the robustness achievement, measuring and maintaining of performance variation is required. For this, production has to note, not only the DP achievement but also "how that DP is impacting on performance", requiring a change to the information flow from design to manufacturing. Table 1 shows the difference in both.

Sensitivity of an FR to a DP, describes the ratio of how much variation is induced in the FR by variation of DP. This allows the calculation of the DP's contribution to that specific FR achievement [18].

Transfer function describes how the sensitivity of the FR to the DP changes for different values of the DP. If the transfer function is linear then the sensitivity will remain constant for any value of the DP. This allows an estimation of the exact change required in DP to achieve the required improvement in FR.

Couplings/Axiomatic condition describes how all of the FRs are influenced by different DPs. This enables the FRs to be balanced while applying changes in DPs adding to the transparency of the effects of adjusting the DPs.

Table 1 Robustness focused organizations need more information flow than those with a traditional quality focus

Quality	*Robustness*	*Purpose*
1. 3D models	1. 3D models	For making tools and fixtures
2. Drawings with design parameter controls/ specifications	2. Drawings with design parameter controls/ specifications	To measure and maintain
3. Assembly process	3. Assembly process	To establish assembly line
	4. Sensitivity	Count the DP contribution
	5. Transfer functions	Act according to the DP position
	6. Couplings – Design parameters connected with more than one functional requirements	Balancing FRs while changing DPs.

It must be emphasised that individually, each of the above techniques are well researched and various tolerance analysis methods in practice allow for counting sensitivity and contribution of design parameters [19-24].

To calculate the performance of any product picked up from the end of the assembly line, one has to know the measurements of each part from the same assembly. Assembly lines of mass production work on different logistic principles, for example, in a Just In Sequence (JIS) system; parts from manufacturing units reach the assembly line in the same sequence as the assembly plan. In these systems part measurements happen at the part manufacturing location only. In the present globalized situation, often parts come from overseas. Measurement data captured at various locations needs to be bought together and analysed. Advancements in PDM/PLM tools in addition to part making and identification technology, make monitoring and adjustment approaches such as the one being proposed in this article, both a feasible and probable capability in the near future.

3. Results and discussion

The principle of robustness monitoring system is "predicting functional performance by calculating with actual parts and processes achievement using their relationships ". From design, FRs and DTs flow down the system to DPs. Further relationships from DPs to PPs are generated through tools and equipment design. The assembly process gets defined at design but APs are derived from assembly line design.

Linking PPs – DPs – APs – DTs – FRs of the product in an easy readable form is the backbone of the monitoring system. This also aims to display the variation contribution of each parameter. This indicates HOW product performances vary and directs WHICH parameter and HOWMUCH to adjust in order to compensate. Furthermore monitoring system gives the overview of HOW TO CHANGE by selecting the quickest and minimum number of parameters. A schematic representation of the robustness monitoring system is as shown in Fig. 5.

The robustness monitoring system communicates three levels of information.

Level1 – Shows the status of final product Dimensional Targets and Functional Requirement. Mathematical relationships of DTs and FRs are derived from design philosophy.

Level2 – Shows the status of Design parameters. The relationship between Level1 and Level2 is derived through Assembly parameters. These relationships are determined from assembly equipment design. Outsourced parts are maintained by suppliers within specified limits and join at this Level. These DPs are known only once they have arrived and cannot be changed further.

Level3 – Shows the status of Process Parameters as controlled, semi and uncontrolled. Controlled refers to production floor opportunities like, Speed, Feed, injection pressure, etc. Those can be varied within a set range of values anytime during production. Semi controlled refers to incoming variables like raw material characteristics which are within specified limits but cannot be changed every day or every instant of production. Uncontrolled refers to parameters that do not have any specifications like ambient temperature, humidity etc. the relationships with Level2 are derived during the Tool design process (Moulds, Dies, etc.) by virtual simulation or physical DOEs before the Start Of Production (SOP).

Fig. 6 shows the robustness monitoring system operating process flow and description of its steps.

This monitoring system is in principle suitable for any type of product and process. Performance variation can be minimised using this tool without the need to tighten parameter tolerances. Once the system established, product upgrades and design improvements can be easily applied. Identifying the robustness monitoring requirements and building its structure is the key step for successful adoption. By linking PPs to their time and cost criteria the monitoring system can incorporate algorithms for suggesting the quickest and cheapest adjustments. Higher measurement frequency and data alignment increases the prediction accuracy.

Higher complexity products, like automotive vehicle production, may need multiple monitoring systems, broken down in to different sets of relevant FRs. Whenever production tools and equipment is replaced, their PP sensitivities are to be updated.

Robustness monitoring to be initiated during design and continued by the development team. This demands a strategic document flow along with stage gate process from design to manufacturing. Alignment between design and process parameter verification at digital and physical levels is critical for system reliability.

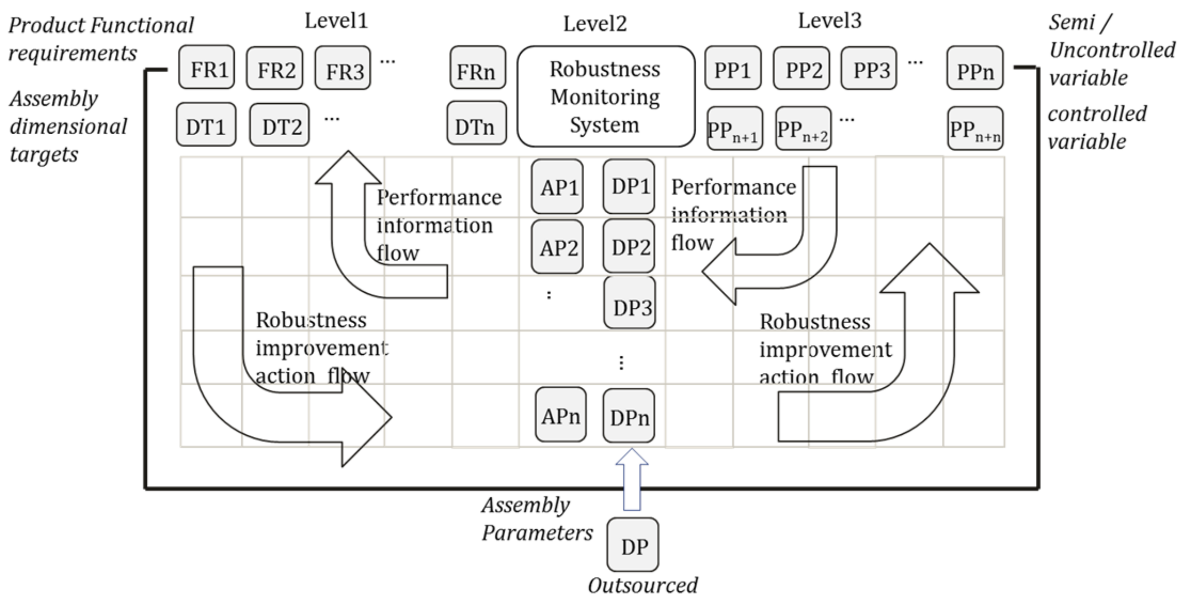

Fig. 5 A schematic representation of the robustness monitoring system connecting PPs and FRs

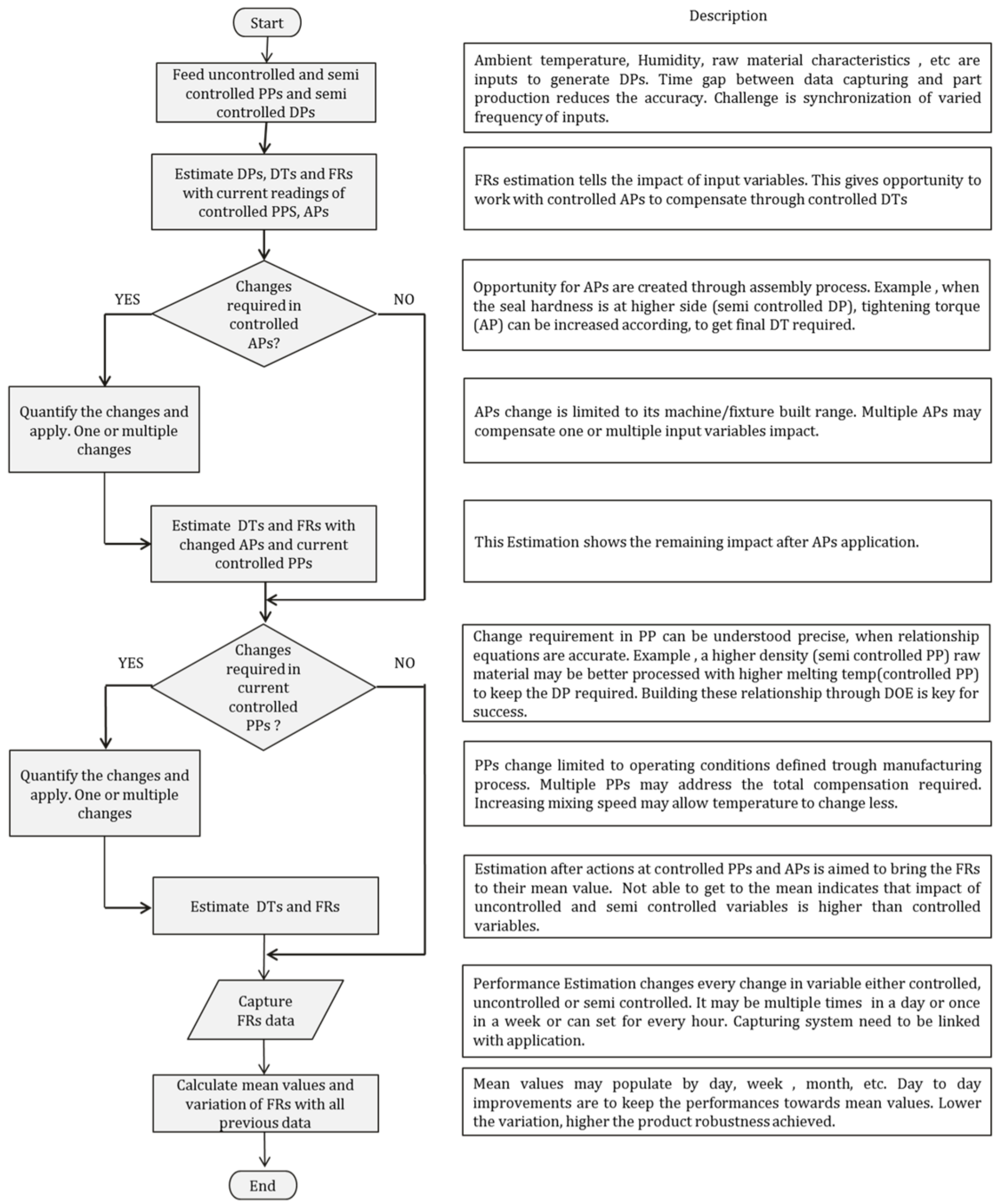

Fig. 6 Monitoring system application flow

4. Case study

A portion of the PRECI-IN injection device concept have been simplified and modelled as a case study to exemplify the application of robustness monitoring system.

4.1 Information from design

This module of injection device is attachable to various types of drug cartridges. A dose setting mechanism allows the user to dial a dose by rotating the scale, which in turn generates tension in a torsional spring. By pushing the button the spring tension is converted to axial movement of piston rod. Fig. 7 shows the assembly and parts with relevant design parameters.

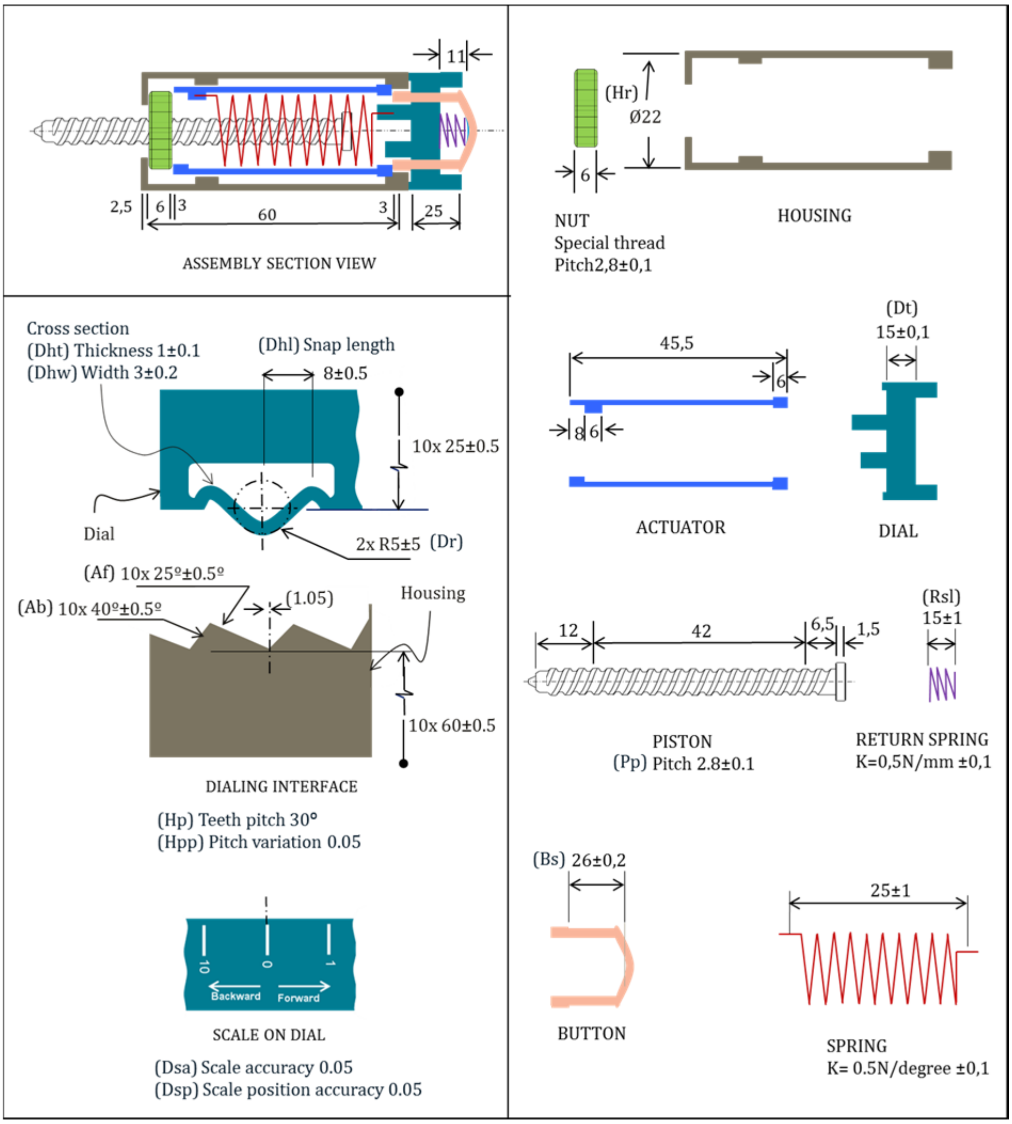

Fig 7 Design parameters information through 3D models and drawings

Functional requirements of Push Button Force (PBF), Dosage Accuracy (DA), Dialling Force (DF), Back Dialling Force (BDF), and Indicator Mismatch (IM) are considered for monitoring. Based on the design, the relationship equations of the FRs to DPs are imported from variation analysis to monitoring system.

4.2 Relationships of PPs to DPs

Data driven production departments will already have good methods to determine the relative influence of the different PPs to the DPs. Dimensional variation of mass produced, injection moulded parts can be modelled based on the analysis of previous experiments determining the influence of different factors. Such experiments are common practice in production departments, although the systematic recording and re-use of data is not done by many companies. All DPs produced in-house are related to their PPs. For e.g. The DP, Pitch of the piston (Pp) from Fig. 7 related to moulding process parameters for that specific tool and machine characteristics simplified as in Eq. 3 Similarly the DP, button snap (Bs) from the Fig. 7 in Eq. 4.

$$\Delta Pp = (2 \cdot 10^{-4} \cdot \Delta MT) + (3 \cdot 10^{-4} \cdot \Delta HP) - (2.5 \cdot 10^{-4} \cdot \Delta CT) + (3 \cdot 10^{-3} \cdot \Delta T) + (5 \cdot 10^{-3} \cdot \Delta H) \quad (3)$$

$$\Delta Bs = (1.4 \cdot 10^{-2} \cdot \Delta MT) + (6.4 \cdot 10^{-4} \cdot \Delta HP) - (1.65 \cdot 10^{-2} \cdot \Delta CT) - (2 \cdot 10^{-2} \cdot \Delta T) + (4 \cdot 10^{-2} \cdot \Delta H) \tag{4}$$

Where, ΔMT, ΔHP, ΔCT, ΔT, and ΔH are change in mould temperature, holding pressure, cooling time, ambient temperature, and ambient relative humidity, respectively.

4.3 The PRECI-IN robustness monitoring system

Fig. 8 shows the experimental monitoring system for six PRECI-IN functional requirements, related to their PPs through DPs.

As the concept does not contain assembly dimensional controls, no DTs are identified in Fig. 8. However the Indicator Mismatch (IM) is a final assembly dimension which is counted as an FR. As all the parts are assembled on to features of other parts, no Assembly Parameters (APs) are used and thus do not feature in Fig. 8. The captured status in Fig. 8 is a single instance of simulated production. The monitoring system treats all controlled variables (Yellow) as opportunities for change. The red cells are the measured but uncontrolled PPs, which can be entered as actual values. The orange cells are DPs of outsourced parts and therefore can only be entered as actual values based on measurement reports. Variation occurring in the FRs can be captured from Level1 cells. To decrease the FR variation, the contribution of each DP and their sensitivity /contribution direction (whether positive or negative correlation) helps to identify which DP to change and in turn, which PP to change. In the current status, BDF (one of FR circled in Fig. 8) is highly deviated by -5.47 N. Opportunities for decreasing the variation is through the DPs, Ab, Hp, Dhl, Dhw and Dht. These DPs are linked to three PPs, MT-S1, HP-S1 and CT-S1. The intention is to change as few PPs as possible to improve BDF, at the same time, affecting the other FRs positive or minimally. Fig. 9 shows the FR improvement after PP change application through the monitoring system. Variation of BDF is reduced to -0.14 by increasing one of PP, MT-S1 (circled) from 90 to 102.

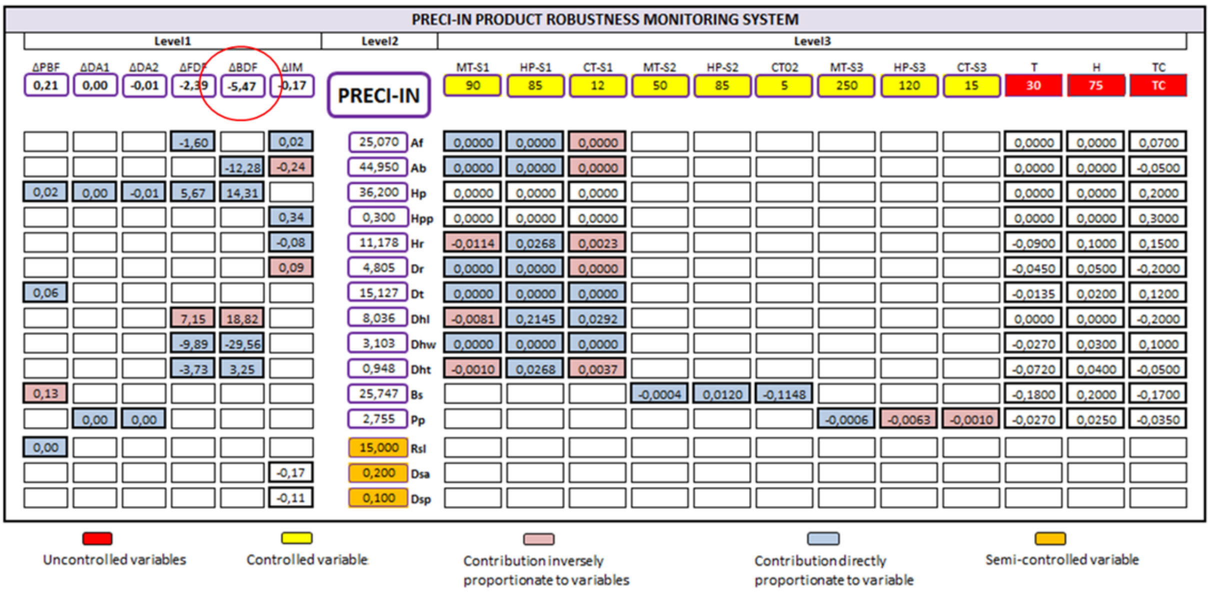

Fig. 8 Monitoring system for six functions of PRECI-IN product concept

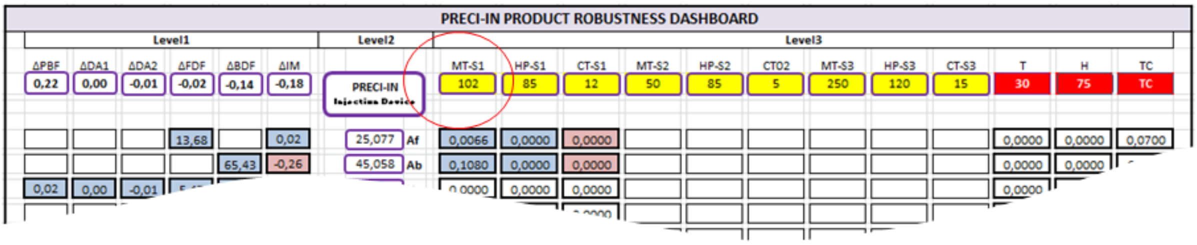

Fig. 9 Monitoring system after FR variation reduction

The robustness monitoring system helps to identify the most effective parameters to act on for FR improvement, which leads to the minimum number of changes. In traditional quality focused approach organizations tend to identify all possible improvements across the production value chain. Brief comparison of both approaches is shown in Table 2.

Table 2 Advantages of robustness focused approach over quality focused

Task	*Traditional quality focused approach*	*Robustness focused approach*
Performance improvement identification	Final inspection/testing	Predictive, before assembly/ manufacturing
Improvement action identification	Root cause analysis techniques	Monitoring system directs the action
Action focus	Applying all possible improvements	Changing minimum parameters
Action reliability	Less, being iterative process	More, due to calculated approach
Time for action identification	Final inspection + Root cause analysis time	Data filling time (instantaneous)

Depending on the quality issue and the complexity of the product, the time saving from using proposed monitoring system to guide corrective action could be anything from hours to months. To give some examples of the impact, two quality experts were interviewed from different industries to describe the procedure and the time required to achieve typical quality aims. To ensure a reasonable comparison, projects were chosen with similar characteristics to PRECI-IN, in terms of, the number of components, plastic components and the forces involved. The context were also similar, where the performance was with-in specification but improvement intended. Table 3 describes the main differences between the PRECI-IN case and those described in the interviews. The *industry* influences the analysis procedure and time for concluding actions. Assembly cycle time indicates the minimum time required to make a PP change visible in the final product for each iteration. The *production volume* impacts the time available for iteration, The percentage of *in-house manufacturing* determines the number of controlled PPs. The time to conclude action and the *# of DPs and PPs* acted on were recalled/estimated by the interviewees.

Analysing the nature of iterations in both the cases reveals the missing information, which can eliminate the iterations is shown in the Table 4.

Table 3 Average time taken and number of DPs and PPs acted on in various industries

Industry	*Production*	*Cycle time*	*In-house manufacturing*	*Time for concluding action*	*No. of DPs acted on*	*No. of PPs acted on*
Automotive	6000/day	4 h	10 %	7 days	2	7
Home appliances	300/day	3 h	10 %	7 days	1	3

Table 4 Iterations and their related information missing

Industry: Improved FR	*Concluding DPs*	*Concluding PPs*	*Missing information*
Automotive: Gap uniformity around the switch bezel found higher side in door trim assembly	Iterative process : First – Bezel hook position changed equal to the non-uniformity observed. Second – Higher pressure on snap opposite to the hook lifted the bezel up and flushness disturbed, to reduce the stress snap interference reduced. Third – Uniformity not improved as expected, once again hook position changed.	Iterative process: First – One uncontrolled PP has been changed Second – Second Uncontrolled PP has been changed Third – First changed PP is changed again. Along with three of controlled PPs also adjusted.	1. No DP to FR relationships are defined. 2. Specific DP change impact on other FRs is not known 3. Contribution of Uncontrolled and controlled PPs together in DPs is not clear.
Home appliances: Mixer-A load transmission gear life is noted lower side of its defined warranty.	Iterative process: First – Gear strength increased by changing the material grade. Second – As the gear life not increased as expected, material grade changed again for higher strength Third – Once again improved the material with latest grade.	Iterative process: At every time of grade change, three PPs are re-established.	1. No FR to DP relationships established, No DP contribution analysis could perform. 2. No performance linkages available for narrowing correct DP.

4.4 Predictability accuracy

The accuracy of prediction for any product at any instance of production depends on how frequent the uncontrolled and semi controlled variables measurements are available. If we are able to capture variation data for every part, with the monitoring system it is possible to predict the performance of every product coming off the line. When the variable represents a batch of parts, estimation accuracy is directly proportional to the batch variation. This is similar for uncontrolled PPs, such as ambient temperature and humidity. If the ambient temperature is noted for every 2 °C change, prediction accuracy is affected by 2 °C. Table 5 shows the list of variables influencing prediction accuracy.

Table 5 Prediction accuracy of various performances influenced due to semi controlled DPs and uncontrolled PPs

Performance variation	*DP variation acceptance within the batch*			*PP variation with in frequency*		*Total influence on prediction accuracy*
	Rsl 0.4 mm	Dsa 0.05 mm	Dsp 0.05 mm	AT 2 °C	AH 1 %	
ΔPBH	0.20	NA	NA	0.03	0.02	0.25
ΔDA1	NA	NA	NA	0.00	0.00	0.00
ΔDA2	NA	NA	NA	0.10	0.01	0.11
ΔFDF	NA	NA	NA	0.40	0.49	0.89
ΔBDF	NA	NA	NA	1.41	1.04	2.45
ΔIM	NA	0.10	0.10	0.10	0.00	0.30

5. Conclusion

Proposed monitoring system found capable to reduce final product performance variation dynamically by providing most effective adjustments in process parameters. This is analysed for injection moulded parts assembly case. Adapting this monitoring system as part of a project from the beginning allows ensuring the correct information flow from design. This shifts the present paradigm of quality control at mass production from part dimensions to product performance.

Same tool can be further extended to estimate customer / stakeholder perceived quality loss, due to variation which can be defined at the beginning of the product development [25].

Some challenges that left for future work are:

- Deriving relationship equations at the manufacturing stage demands conscious experiments and data validation. The challenge of applying uncontrolled variables in the experiments reduces the accuracy of relationship equations.
- Industry follows several approaches to calculate contribution and sensitivity. This may lead to different interpretations of the same information.

Acknowledgement

The authors would like to acknowledge Novo Nordisk for the research funding under the DTU-Novo Nordisk Robust Design Programme. Authors thank the quality engineers and their respective organizations that participated and evaluated the research proposal.

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APEM journal
Advances in Production Engineering & Management
Volume 11 | Number 3 | September 2016 | pp 173–182
http://dx.doi.org/10.14743/apem2016.3.218
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Business plan feedback for cost effective business processes

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A B S T R A C T

Business planning encompasses all the goals, strategies and actions to ensure company's business survival, prosperity, and growth. Literature review and analysis of business processes of production systems show that the business plan is considered as a rigid system, even though it is being prepared in a world of constantly changing business conditions. The possibility of correction of a business plan that is being realized in the course of a year is only a theoretical possibility, and the introduction of a feedback system as an element of correction remains only as an idea. The aim of this paper is to propose and introduce a system in the business technology that would be similar to the designing principles for automated technical systems. In the paper an original business planning model with feedback is presented. The model includes planning, monitoring and harmonization of business operations. It is appropriate for unstable conditions too, regarding the essential influences from the business environment, thus adapting the company's operations. It could be used in small- and medium-sized companies, in industries of all types. The model enables the assessment of present and future business results. Verification of the model has been successfully carried out at three levels.

A R T I C L E I N F O

Keywords:
Cost-effectiveness
Feedback
Business plan
Business process
External and internal influences

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Article history:
Received 21 March 2016
Revised 3 August 2016
Accepted 16 August 2016

1. Introduction

Changes of business conditions affect the mechanism of income formation. This results in lower profit which sometimes leads to the loss and, not so rarely, to the shutting down of the production system. The consequences of deteriorating business conditions can be measured and, based on this, changes of some business conditions can ensue. The result of the changed business operation is calculated and if the correction is not satisfactory, the next correction is automatically proceeded with. The main elements that require correction are: cost reduction, production increase, reduction of staff, reduced salaries, etc. The preparatory work included the analysis of business operation of fifteen small and medium-sized enterprises, and a model was made based on their financial plans, planning systems, and business results. One of these companies was subjected to a test (theoretical) calculation of model application.

The main question of this research is: is it possible to develop a new model of planning, monitoring and coordination of industrial enterprises in the course of the fiscal year, as a function of the character and intensity of the impact of changes in the environment?

In accordance with the defined problem, the subject of the research presented in this paper is business planning of the industrial enterprises in the conditions of dynamic changes, and harmonization of business operations with the changes taking place in the everyday environment.

The objectives of the present study were to:

- identify the key influences from the environment and mechanisms of business operation corrections for each influence separately, providing the appropriate mathematical calculations,
- defines the procedures of harmonization of plan and business operations,
- propose a scientific description of the new model of planning, monitoring and harmonization of business operations.

The goal of the research activities was to develop a model of planning, monitoring and harmonization of operations which will apply the feedback mechanism to harmonize the operations with influences from the environment, thus adapting the company's operations with negative or positive impacts from the environment.

2. Literature overview

The literature covering the subjects of business planning distinguishes between the business planning process which is continually implemented throughout the year, i.e. procedures used for developing the plans and results of business planning [1]. In addition, there is literature that emphasizes the importance of the process of business planning because it helps understand the business and offers the possibility of learning [2].

Planning enables enterprises to have control over the achievement of the objectives. In the case of deviations from the plan, the causes of those deviations can be identified and incorporated into future business operations [3]. The supporters of business planning emphasize that the importance of business planning is particularly evident in a dynamic and unstable environment because it reduces the level of planning uncertainty, facilitates and speeds up the decision-making process [4, 5].

It is a well-known fact that the external environment of the company (suppliers, customers, etc.), as well as the company's employees, often want to see the business plan in order to assess the viability of the business and the level of attraction from an economic point of view. Thus, the process of business planning often has a purely formal character and is a result of certain internal and external pressures due to obligations and legitimacy, instead of being an instrument to ensure better business results. Several authors [6] recognized these tendencies and described them. As it can be expected, the studies dealing with the analysis of the planning system in companies which do not have it as a formal process, determine different effects on business compared to those companies which focus solely on written documentation as a result of following the business plan during the year without reviewing it [7].

The literature proposes two options to help the company ensure continuity and stable operation, that is, its survival and development [8]. The first option proposes greater degree of company's isolation from the environment which implies break of company's relations with its own environment, and, although possible, this does not give a positive result. Another option is to build mechanisms by which the company would regulate its own functioning, i.e. to adapt the operating system to external influences.

The process of adaptation introduces changes in the system in order to achieve stability and continuity of business operations. Adaptability exists in the degree to which the system can survive the changes caused by the external environment, i.e. viability equals the adaptability [9]. Some companies find it difficult to adapt to changes occurring in the environment for several reasons. Companies often do not have developed systems to monitor the changes occurring in the environment, and systems that register different types of impacts. How to implement changes is a key question for every organization or company. Change management (also known as change control) is a professional discipline, which focuses on supporting organizations on their way to a successful transition from a less-than-ideal status quo to a desired future state. Change management is one of the skills every manager should master to a sufficient degree because it represents an integral part of business operations and the process of constant change. It denotes a dispersed set of processes, tools, techniques, methods and approaches for achieving a desired state through change.

Change management approaches have two main objectives:

- to assist the organization in achieving its goals which cannot be attained with the existing organizational structure, functioning and client servicing, and
- to minimize the adverse effects of any changes made [10].

The implementation of lean manufacturing methods is very important for optimization of business processes. Nguyen described the implementation of lean concepts in the context of developing countries [11]. Adjustment of the structure and parameters of production systems should ensure the operation of these systems in more favourable manufacturing and economic conditions [12]. This process is often directly linked with the starting of investment process with the goal of achieving minimal production costs [13].

When it comes to adjusting the mechanisms of company's operations to the changes that result from internal and / or external influences, contemporary literature commonly uses the term of "adjustment of business operations based on the feedback mechanism"; however, it does not offer an elaborate and usable model. As this is the main subject of this paper, the review of relating literature has shown that except the theoretical explanations, there is no operationalization of the subject model.

3. Research

The management and planning models are mainly oriented towards the future, giving priority to the preventive control over subsequent control, with the aim of undertaking the prevention measures before the differences between the planned and actual performance occur.

It is clear that, in a number of cases, the recognition of deviations outside the set limits is much more important because, then, there is a need to redefine the initially established plans and make them more flexible. Thus, the control can be viewed as a causal variable that provides input for improvement of planning and organization in the event of changes in the internal or external environment.

A number of control classifications can be found in literature, and one of them is the division into:

- preventive, feedforward control,
- corrective, feedback control.

The preventive control (feedforward control system) was noted to be more effective when applied to business processes because, in the corrective control system (feedback system), the correction output is returned to the process flow. With preventive control (feedforward system), the unwanted variations of inputs are returned to the flow of inputs to be corrected, or into the process itself, before the output is completed.

Preventive control should be defined by comparing it with subsequent control which has been defined by the authors for different disciplines, but which basic idea can be easily applied in the field of management.

Considering the existence of different views, different approaches and, finally, the existence of different planning systems in companies, a general conclusion is that there is no consistent concept or model of a business plan that can be uniquely determined and widely accepted. This paper is a contribution to the development of this issue, as it sets a model of flexible business planning system based on the principles of feedback mechanism.

The main purpose and objective of a business plan is to define the criteria for basic principles and directions of business operations during a fiscal year so that the fiscal year can end within the limits of forecasted or reduced, but still above the minimum projected profit. As the business plan is typically made before the start of the fiscal, usually a calendar year, there is a fact that that it is very difficult to predict all operating conditions, the intensity of external and internal changes, and the impact on the realization of the business plan during the year.

A complete basic business plan of a production system and its harmonization with altered business conditions can be only considered as a guideline for appropriate corrections of the business system and allocation of resources that the production system has at its disposal.

Bearing in mind that unstable conditions make it almost impossible to predict, with high accuracy, all possible changes of the conditions, the only option that remains is to define the business plan only as the starting framework so that it can be corrected in accordance with the changes of various external and/or internal influences, but it also to show the company's management possible directions of business operations in order to stop, slow down or improve the negative trends of profit and/or other performance indicators.

The basic principles are illustrated with short explanations and illustrations.

This is a flexible business plan that allows introduction of changes based on which the effects on profit are automatically calculated, and it proposes orders for the correction of some elements of the business which makes it a system with the feedback (Fig. 1).

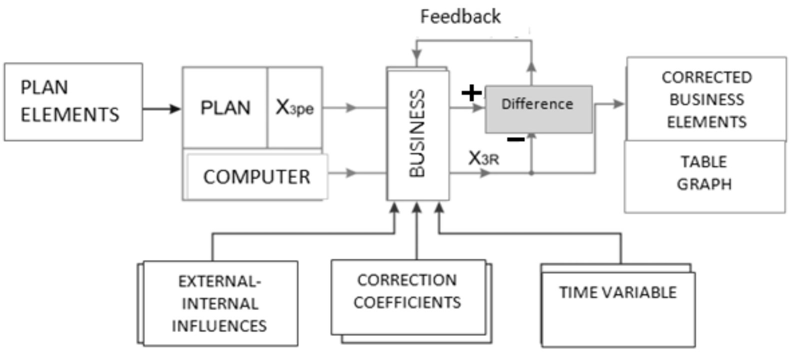

Fig. 1 Block diagram of the mechanism of business planning with feedback

The difference between total income (X_1) and total expenditures (X_2) is the profit of business system (X_{3pl}). External and internal influences affect X_1 and X_2 directly and, through them, reduce the planned profit (X_{3pl}). According to the model developed in the study (PPS), the amount of profit calculated with respect to external or internal type of *„influences“,* and the calculated value for profit (X_{3R}) are automatically introduced as the correction coefficients which number and numerical value show the type of change and average annual profit $K = f(X_3)$. The whole process of calculation of profit and correction coefficients is completed automatically except the occurred changes which are imported manually in accordance with the criteria defined by the model.

The necessary basis for the application of business plan with feedback (PPS) is the preparation of the basic business plan which structure is adjusted to the program of profit calculation with respect to the type and intensity of the change *„EI influence“.*

3.1 Business plan model

Table 1 shows a list and groups of elements of the plan, each with a mark that is used in the overall model of business planning with feedback (PPS) regardless of whether it is an analysis, computer processing or other activities.

Every group of the plan elements is elaborated thoroughly and the plan will include only planned numerical values of the elements that are valid for a company that uses them.

The business plan is done annually (Table 1). It is prepared based on the projections for a business year and, as such, it is unalterable regardless of external and/or internal changes. There is the large number of different negative 'influences' on business operations:

- *external influences*: inflation, reduction in sales volume, increase in energy prices, reduction in product prices, increase in transport costs, increase in contribution and taxes, increase in business costs, increase in loan interests and other,
- *internal influences*: increase in personal incomes, reduction in production, increase in credit debt, inadequate maintenance services, unplanned failure of machines and other.

Table 1 The concept of business plan – basis for the model construction

Mark	Name of variable	Basis for the plan or calculation	
X_1	TOTAL INCOME		Calculated
X_2	TOTAL EXPENDITURES		Calculated
X_{21}	*BUSINESS EXPENDITURES*		Calculated
X_{22}	*INVESTMENTS*	Planned	
X_{23}	*FINANCIAL EXPENDITURES*		Calculated
X_{24}	*OTHER EXPENDITURES*		Calculated
X_3	PROFIT $X_1 - X_2$		Calculated

It is certain that a unique automatic program cannot include all the influences on business operations because of both a large number of variables and the fact that those variables do not often act individually. Usually, there is a combination of two or three variables at the same time and they often have different influence on business operations with the same performance. This way, for example, the following can be combined: reduction in sales volume and price reduction.

In addition, the degree of change of different EI influences on business operations can neither be equal.

By combining different number of influences of varying intensity and level that can be made on business operations, then thousands of different groups of influences can be obtained which would make the planned and designed model completely useless, not only because of a large number of combinations but because of the numerous mistakes that can be made in case of development of the model itself and definition of initial numerical values of influences and numerical valorization of the degree of their impact on business operations.

The selected '*influences*' can be divided into two groups and are included in the business planning model with feedback (PPS) in the data processing which is used for:

a) automatic calculation of the profit with feedback (reduction in sales volume, production price, increase in costs of business operations) and
b) analysis of EI influences only for the calculation of the future business results on a one-time basis without any corrections and feedback (increase in the price of raw materials and energy prices, increase in employees' incomes, increase in values of external services and internal costs).

3.2 Definition of typical zones of profit and introduction of business correction coefficients

The basic criteria for business performance – profit (X_3) in PPS model is determined by five typical levels and four zones of profit (Fig. 2).

The set levels and zones of profit are defined in the PPS model based in Fig. 2. However, considering the fact that it is an open model, the levels and zones can be changed in accordance with the concepts of company's management or specific position of a company on the market.

A. Start: Planned profit X_{3R} – the first zone at the beginning of the planned period X_{3pl}.

B. Second profit level which is in compliance with the established relationship between the calculated and planned profits:

$$X_{3r1} = 0.55 \cdot X_{3pl} \quad (1)$$

C. Third profit level complies with the established relationship between calculated and planned profits:

$$X_{3r2} = 0.30 \cdot X_{3pl} \quad (2)$$

D. Fourth profit level complies with the established relationship between calculated and planned profits:

$$X_{3r3} = 0.15 \cdot X_{3pl} \quad (3)$$

E. Fifth profit level complies with the established relationship between calculated and planned profits:

$$X_{3kr} = 0.10 \cdot X_{3pl} \quad (4)$$

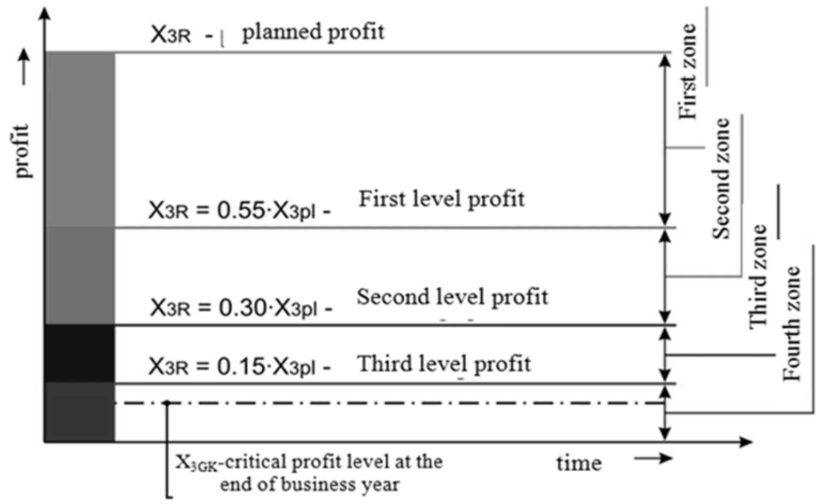

Fig. 2 Typical levels and zones of profit in case of EI influences (X_{3pl} – planned level of profit; X_{3R} – calculated level of profit 1, 2 or 3; X_{3R} – critical level of profit)

Coefficients for defining the profit levels are provisional (0.55, 0.30, and 0.15) and can be changed.

Four zones of profit, which depends on the intensity of EI influences, are defined within the specified values (Fig. 2) and this paper focuses only on the summary of the research (model):

- ***first zone*** in which the calculated profit ranges: $0.55 \cdot X_{3pl} \leq X_{3r} \leq X_{3pl}$ – a zone in which *no correction of business operations is performed*,
- ***second zone*** in which the calculated profit ranges: $0.3 \cdot X_{3pl} \leq X_{3r} \leq 0.55 \cdot X_{3pl}$ – a zone in which *the first level of correction of business operations K*1 *is introduced on a one-time basis* based on the criteria defined for each EI influence separately,
- ***third zone*** in which the calculated profit ranges: $0.15 \cdot X_{3pl} \leq X_{3r} \leq 0.30 \cdot X_{3pl}$ – a zone in which *the second level of correction of business operations K*2 *is introduced on a one-time basis* based on the criteria defined for each EI influence separately,
- ***fourth zone*** in which the calculated profit ranges: $0.00 \cdot X_{3pl} \leq X_{3r} \leq 0.15 \cdot X_{3pl}$ – a zone in which *the third level of correction of business operations K*3 *is introduced on a one-time basis* based on the criteria defined for each EI influence separately; the critical level of minimum allowed profit X_{3kr} is in this zone.

At the third level of correction (the fourth zone of profit), the system of feedback is introduced based on three bases:

- ***first***, when, after the introduction of the first corrective measures (*K*3.1), the profit remains in the fourth zone and does not pass into the second zone, the correction is repeated (*K*3.1),
- ***second,*** when, after the introduction of the first corrective measures (*K*3.1), the profit changes and passes into the third zone and during further business operations it again enters the fourth zone – the second corrective measures are introduced (*K*3.2), and
- ***third,*** when the profit is below the critical level X_{3kr} and when the third level of corrective measures is introduced, comprising repeated corrections *K*3.1, and then *K*3.2 until the profit is increased above the critical level.

The reduction of the planned profit X_{3pl} to the level indicated later in Fig. 4 as $X_{3.12}$ is the result of EI influences and depends on the *SPV* coefficient. When the decrease in the profit is so large that the profit passes into the second zone ($0.55 \cdot X_{3pl} \leq X_{3R} \leq X_{3pl}$), the business operations are corrected based on the defined criteria.

A new variable is introduced in the business planning model with feedback: *time and duration of the change*, and then it is connected with the *calculated results of business operations* which are presented through the achieved profit. This is done because of adverse effects which, besides they appear in different periods of a year, never change evenly during a year, 1 %, 2 %, 3 % (for example, there is an increase of 1 % every month). When we take into account the time constant, we should bear in mind that the change in business plan could be analyzed ahead by defined time cut-off points and/or at the moment of change.

A system of parallel monitoring in time (for example, every month) and at the time of change have to be applied for the complete *PPS* model application. Therefore, conceptually different profits can be defined:

- *planned profit* (X_{3pl}),
- *present value* of the profit in the month when such a change occurred or at any other cut-off point X_{3R},
- *average profit* of a company in the period *preceding the change* (X_{3P}), including the profit in the month when the change occurred (analyzing the influence of the change on the profit in the preceding period), and
- *average profit* of a company *during a year* (X_{3G}) under the conditions when the last change occurred in the current year (analyzing the influence resulting from the change on the business operations throughout a year).

Mathematical interpretation of the influence of 'time and duration of change' variable on the profit for all three methods is presented graphically in Figs. 3 and 4.

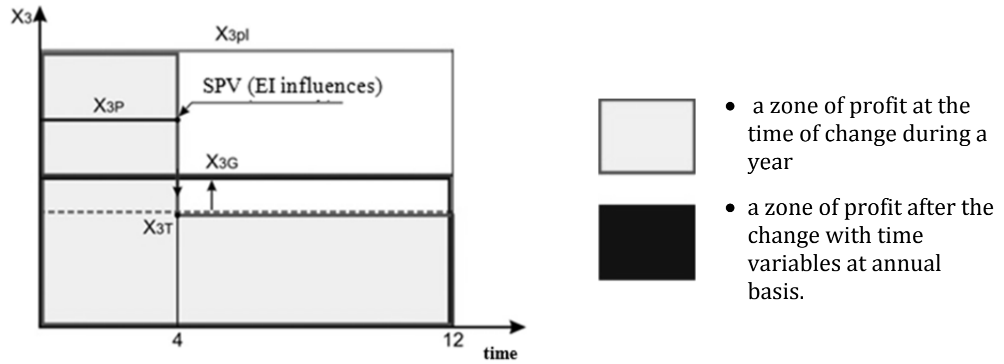

Fig. 3 Graphical overview of defining a profit

Fig. 3 shows an average profit during a year (distributed to 12 months), X_{3G}.

The numerical value at the cut-off point (i) at annual basis is calculated based on the following equation:

$$X_{3Gi} = \frac{X_{3G(i-1)} \cdot m}{m_G} + \frac{X_{3Gi} \cdot (12 - m)}{m_G} \tag{5}$$

where i is a cut-off point during which a profit is calculated at annual basis, m is a number of months of business operations to the i-cut-off point, m_G is a number of months in a year (m_G = 12), X_{3Gi} is the calculated level of profit at the i-cut-off point of change in EI conditions, obtained as a difference between total revenues and total expenditures, $X_{3G(i-1)}$ is the calculated level of profit at previous cut-off point of change in EI conditions.

The calculation of change in profit is presented graphically in Fig. 4. Fig. 4 shows the calculation of corrections of business operations under the modified business conditions which, in the planned year, lead to the fall in planned profit during a year at all levels. When the business conditions, which have adverse effects, change and the profit falls from X_{3pl} to $X_{3.11}$ (at annual level, but not below the limit which is marked with the first level $X_3 = 0.55 \cdot X_{3pl}$), the first correction $K1$ is made, and then by applying the mechanism of calculation based on 'time variable', the planned profit falls annually (or it does not fall) to the level $X_{32.1}$ at annual basis. In case that, for example, the business conditions change during a year and the profit falls under the level 2 ($X_{3R} = 0.30 \cdot X_{3pl}$), then the correction is made based on the criterion defined as $K2$. If the hypothetically defined fall in profit continues during a year, then the correction $K3$ is made.

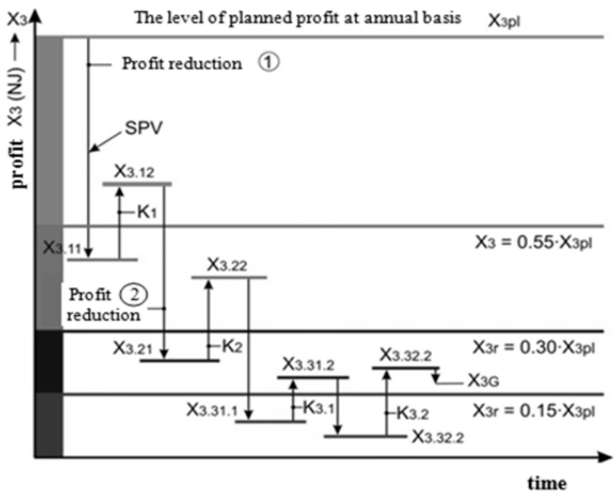

Fig. 4 The change in designed profit due to EI influences and mechanisms of corrections of business operations – *K*1; *K*2; *K*3.1; *K*3.2

All impacts on business, which lead to the fall in profit, and correction coefficients are clearly marked within the model and they are only numerically valued due to mathematical processing of the model and they can be easily defined in line with the business conditions of the company which implements the described model. This has already been done because, for example, the increase in the fuel price has different influence on business operations of the transportation company then on the business operations of the metalworking company.

3.3 Mathematical statement of business plan elements and procedures of corrections of business operations

In mathematical statement of the PPS model, elements of the plan can be divided into several groups with the same mechanism of operation:

- Elements of the plan that change due to external-internal influences (through changes defined as *SPV*). Those are the initial changes and their numerical value follow the change of EI influences.
- Elements of the plan that change (through *PKP* coefficient) in compliance with the change of EI influences, follow it because of the plan correction, and they are introduced when the profit is in the zones 1, 2 or 3 (presented in Fig. 2). Those are the elements of correction of costs which aim is to achieve the harmonization between the reduced and planned (X_3) profits. The numerical value of these variable coefficients of the plan correction (*PKP*) follows, with the same percentage, the change in EI influences expressed through *SPV* coefficient.
- Elements that are defined and constant until the next planned change (through *KPK* coefficient), the so-called constant elements ($KPK1 = 1 \cdot Y$, that is, $KPK2 = 0.5 \cdot Y$; *Y in %*) and corrections of plan costs with the aim of adjustment are reduced by the planned (X_3) profit. The introduction of *KPK* is not related to the change in *SPV* but to the moment the profit enters critical zone 3.

Mathematical statement of a single case of impact – reduction in the product price:

$$X_3 = (X_{11} + X_{12}) \cdot SPV - ((X_{211} + X_{212} + X_{213} \cdot PKP + X_{214} \cdot KPK + X_{215} \cdot PKP) + (X_{221} + X_{222} \cdot PKP) + (X_{231} \cdot PKP + X_{232} \cdot PKP + X_{233} \cdot PKP + X_{234} \cdot PKP + X_{235} \cdot PKP)) \quad (6)$$

where:

$$SPV\ (PKP; RKP) = 1 - \frac{Y}{100} \quad (7)$$

and Y is a change (reduction **– ;** increase +) in %, SPV is a constant change in business operations, initial influence, PKP is a variable coefficient of correction of business operations, KPK is a constant coefficient of correction of business operations, X_{11} are the revenues from domestic market; X_{12} are the revenues from foreign market, X_{211} are the costs of raw materials from domestic market, X_{212} are the costs of raw materials from foreign market, X_{213} are the production services, X_{214} are the personal incomes, X_{215} is the investment and development, X_{221} are the costs of credit, X_{222} are other financial expenses, X_{231} are the costs of fuel and energy, X_{232} are the costs of transportation services, X_{233} are the maintenance costs, X_{234} are non-production services, X_{235} are other expenses.

4. Concluding remarks

A flexible planning system, which follows the logic of thinking, that is, understanding of the company's management, should result in generally accepted business philosophy around the world – profit maximization.

The research on needs, possibilities for design and implementation of business planning model with feedback were carried out based on the formulated hypotheses.

The achieved level of research in the field which is the topic of this paper (business planning with feedback) was analyzed during preparatory works. A large number of papers deal with the problem of doing business in unstable conditions and demonstrate the need to implement business planning with feedback. Some principles are mentioned, however, the designed model, or its preliminary version, could not be discovered. In the paper, this idea was developed and designed in a model-based research.

Verification of a company's business planning model with feedback (PPS), as a process of adjustment of company's business operations with plans under the influence of environment, was carried out at three levels. The aim of the verification was to:

a) Include the most important elements of business operations in the plan which was defined as alterable for companies of different size and configuration,
b) Examine the possibilities for implementation of model in the company's business,
c) Analyze the achieved results, assess their real meaning and application in current business operations,
d) Examine the possibilities for implementation of the model in the process of assessment of business results in the future, assumed business conditions and anticipated influences from the environment.

Based on the conducted research, the goal to develop a verified model for business planning, monitoring and harmonization has been achieved.

The model proposed in this paper can be upgraded in various ways. One option is to upgrade this model with the change management model.

Given the complexity of the problem, the dynamics of changes in the environment and lack of the correct solutions in the literature, even in its initial form, the aim is to continue with the research on this topic with focus on:

- Programming of the business planning model with feedback (PPS) in some of the software applications which configuration is regulated to solve the mentioned problem.
- Implementation of the business planning model with feedback (PPS) in a few selected typical companies, according to which the entire process of planning, monitoring of changes and results of business operations would be adjusted with the model.

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APEM journal

Advances in Production Engineering & Management
Volume 11 | Number 3 | September 2016 | pp 183–191
http://dx.doi.org/10.14743/apem2016.3.219

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Studies of corrosion on AA 6061 and AZ 61 friction stir welded plates

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ABSTRACT

A remarkably new welding process, namely friction stir welding (FSW) has reached a tremendous research interest on the present decade due to bonding of similar or dissimilar materials at solidus state. This welding technique is environment friendly and versatile. In specific, FSW can be used to join the high strength aluminium alloys and other dissimilar alloys that are difficult to weld by conventional fusion welding. The process parameters have a major role in changing the characterisation of the joint. In this work, three parameters of the weld, namely rotational speed (rpm), axial load (KN), and weld speed (mm/min) are considered. Three pairs of AA 6061 and AZ 61 plates were welded with three different sets of these parameters. The welded zone was immersed in corrosive solution of NaOH for six months period. Corrosion behaviour was studied with the help of SEM and EDAX. Through this investigation, the importance of weld parameters control for the study of effects on the susceptibility for corrosion on the welded region can be sought.

ARTICLE INFO

Keywords:
Friction stir welding
AA 6061
AZ 61
Tool geometry
Corrosion behaviour

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Article history:
Received 15 December 2015
Revised 24 May 2016
Accepted 16 June 2016

1. Introduction

The corrosion is caused by the chemical and/or electro chemical reaction of metals with environment. Due to the conservation and safety requirements of alloys the need of investigation on corrosion arises. To reduce the impact of corrosion, corrosion engineers and scientists made a major investigation on the corrosion of piping, bridges, marine structures, ships, metal components of machines and so on to reduce material losses and to utilize the conservation metal usage. Corrosion study is vast important in the safety point of operating equipment. Loss of metal by corrosion is not only affecting the physical strength but also raising the cost consumption for the replacement of the corroded metal structures within its useful life. In addition, rebuilding of corroded components involves further investment of all the men, materials and machines resources.

It is well known that aluminium is one among the most abundant metals in nature. It is ductile in mechanical characterization and can be easily cast and machined. Adequate properties kept aluminium as a different alloy from other alloys. First, it is lighter compared to all other engineering alloys except magnesium and beryllium. It has a density value of about 2990 kg/m^3. A second noted property of aluminium is its electrical and thermal conductivity. The third property which is made the most responsible for the selection of aluminium alloys is their corrosion resistance. Resistance welding can be preferred on some aluminium alloys but the surface preparation is expensive and the formation of surface oxide being a major problem.

The magnesium series alloys are often used in automobile applications, marine and aviation due to their high strength to density ratio. The challenge on making fatigue and fracture resistant welds in aluminium alloys have been found wider use for joining aerospace structures. In the case of magnesium alloy, if the aluminium content is a dominant alloying element then it is characterized as magnesium alloy AZ61.

Aluminium and magnesium are found as one of the lightweight alloys with noted corrosion resistance with good thermal and electrical conductivity. The remarked corrosion behaviour of aluminium is effected by the small amounts of impurities present in the metal; all these impurities, with the exception of magnesium which tends to be cathodic to aluminium.

The distinct applications of aluminium alloys in aerospace and automobile industries directs the choice on welding behaviour and selection of most appropriate welding method. Aluminium alloys of 2xxx, 6xxx and 7xxx series have been adopted for remarkable usage in these industries [1]. This transpires the desirable strength to weight ratio, good form ability, appropriate weld ability and acceptable corrosion resistance [2]. According to the particular application, corrosion behaviour have a major role on the strength of welded joint [3].

Magnesium (Mg) alloys are considered to be one of the light weight metallic alloys due to its higher mechanical stiffness and lower density which is around 1.74 g/cm^3 [4]. In the presence of seawater, the benefits of magnesium are distinctive by high corrosion rate compared to aluminium or Steel [5]. The areas unexposed to the atmosphere such as electronic boxes and car seats have been regulated its usage of alloy by high corrosion resistance of magnesium [6, 7].

Earlier investigations on the tool geometry design were aimed on optimization of the tool pin with respect to mechanical properties and micro structure [8-11]. Recent investigation on corrosion behaviour on aluminium alloy 6061 reveals that control of grain size enhances the susceptibility to corrosion and intermetallics dominates the role on formation of galvanic corrosion couples [12]. Also as per microstructure analysis on corroded surfaces of Al-Zn-Mg aluminium alloy 7039 FSW joints, the different weld zones like HAZ, TMAZ and NZ are compared for corrosion behaviour. By comparison the Heat Affected Zone (HAZ) was more susceptible to corrosion [13]. The studies focused to the effect of tool pin profile and change of weld parameter on the corrosion behaviour and micro structure on corroded surface are less [14]. The current investigation is with corrosion behaviour of FSW joints with different weld parameter for threaded pin profile.

2. Friction stir welding

2.1 Process

The basic principle of FSW is concerned with a metal flow of metal/alloy to be welded by a combination of axial load and rotational as well as transverse feed by a rotating tool which is having a specifically designed probe (pin) and shoulder profiles. The tool preserves two primary functions such as heat input on the metal to be welded and metal flow mechanism in the joint. The heat input is generated by friction on the tool and the metal/alloy interface. The localized heat generation softens the metal/alloy which is welded closer to the probe and combination of tool rotation speed and transverse speed plays major role in the metal flow. Because of different geometrical features of the tool profiles and the metal flow intense plastic deformation set up. Due to the efficient utilization of energy, environment friendly feature and versatility the FSW is considered to be the most effective metal joining method in the recent decade.

2.2 Tool geometry

The design/selection of tool geometry is the influential aspect of heat input in FSW process. Since tool geometry have a critical role in material flow and in turn it governs the heat generation rate at which FSW is processes [15]. An FSW tool consists of a shoulder and a probe (pin) as shown schematically in Fig. 1.

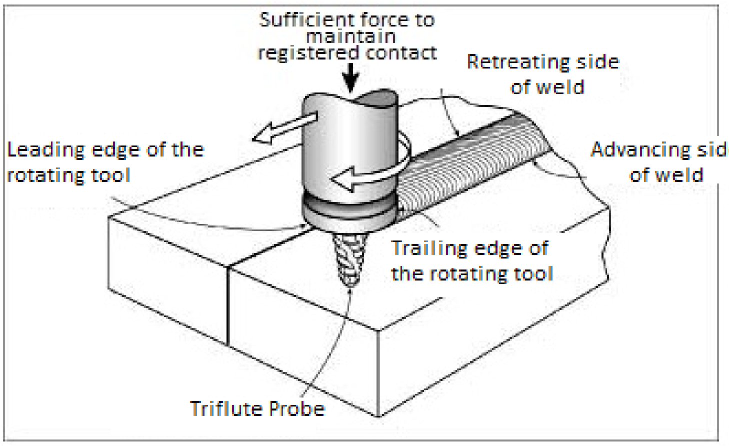

Fig. 1 A schematic view of friction stir welding [16]

As per literature, the tool has two primary functions one is a mechanism of material flow, and the other one is localized heating. In tool plunging, the heat generation is primarily due to the friction on the interface of tool and base metal/alloy. Later additional heat results from plastic deformation of material. From the heat generation point of view, the relative size of tool probe and shoulder is significant. According to the recent numerical evaluation the weld nugget zone experiences a serious compression and shear [17]. The uniformity of micro structure and physical properties are affected by the tool design. Generally a threaded cylindrical pins and concave shoulder are used. Complex features on tool profile have been added to improve material flow and reduction of process loads. Fig. 2 shows the tool geometries tested for the corrosion behaviour.

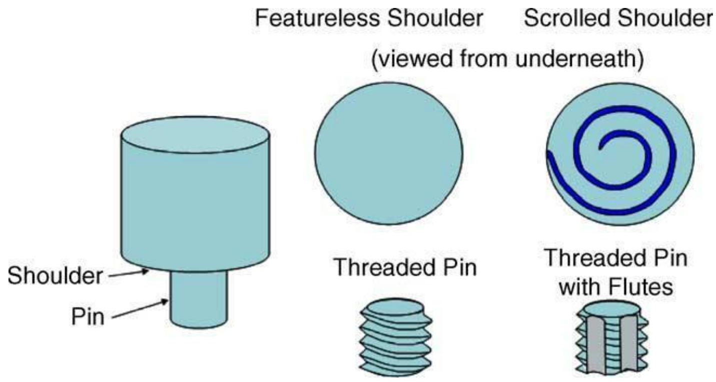

Fig. 2 Line sketch of friction stir welding tool used for the butt joints of AA 6061-AZ 61 alloys for corrosion behaviour study [15]

2.3 Welding parameters

As per the trend on weld parameters of FSW for investigation tool rotation rate (v, rpm) and tool traverse speed (n, mm/min) are the most involved along the line of joint. The rotation of tool with some axial load results in stirring and mixing of base metal/alloy to be welded and the translation of tool pushes the stirred material from the advancing side to the retreating side. Higher tool rotation rates set up a higher temperature because of higher friction and results in more influences on stirring and mixing of material. However, the friction of tool with weld metal is responsible for the heating [18].

3. Experimental work

The corrosion behaviour was tested experimentally for the components which are joined with different weld parameters using friction stir welding.

3.1 Welding

Two alloys were chosen for the current corrosion investigation of FSW butt joint. One is from the AA 6XXX series – AA 6061. The other one is from the magnesium alloy series – AZ 61. Three plates each of 5 mm thickness of these alloys were taken. The dimensions of the plates are 100 mm × 100 mm. The friction stir welding of these plates was carried on these plates using three different weld parameters listed as in Table 1.

Table 1 Weld parameters of the three samples

Weld parameters	Samples		
	A	B	C
Load (kN)	10	12	16
Rotational speed (rpm)	400	600	1200
Transverse speed (mm/min)	30	40	50

Thus, three different samples were prepared. These samples were left as such for six months. During this aging period, the atmospheric corrosive agents will affects the defective surfaces on the welded region, if any. The aged plate is then taken for further analysis.

3.2 Corrosion testing

To examine the effect of corrosion on the weld it was decided to immerse the welded region in strong alkaline solution for specific time periods. Then NaOH solution of pH 8 was prepared. The welded portion of each sample was cut into five pieces of 10 mm width, Fig. 3. These were separately immersed in 100 ml of the NaOH solution prepared. They were immersed for six month time periods. After removing the samples from the solution, they were washed in distilled water. Then they were washed with acetone to prevent further corrosion of the samples. These samples were concealed in airtight covers and labelled. A few photographs of the samples tested are shown in the Fig. 4.

Fig. 3 Welded sample: A cut into pieces for corrosion testing

(a) (b) (c)

Fig. 4 Welded samples dipped in NaOH: (a) sample A (FSW joint with parameters axial load 10 kN, rotational speed 400 rpm and transverse speed 30 mm/min); (b) sample B (FSW joint with parameters axial load 12 kN, rotational speed 600 rpm and transverse speed 40 mm/min); (c) sample C (FSW joint with parameters axial load 16 kN, rotational speed 1200 rpm and transverse speed 50 mm/min) [19]

3.3 Microscopic examination

Each specimen was examined under metallurgical microscope. The effects of corrosion were hard to find under it. So the samples were examined with a Scanning Electron Microscope (SEM). The images were taken at the portion where the welded region met with the parent metal and at the centre of the welded region. The Energy Dispersive X-Ray Analysis (EDAX) was also carried out for the welded and corroded region.

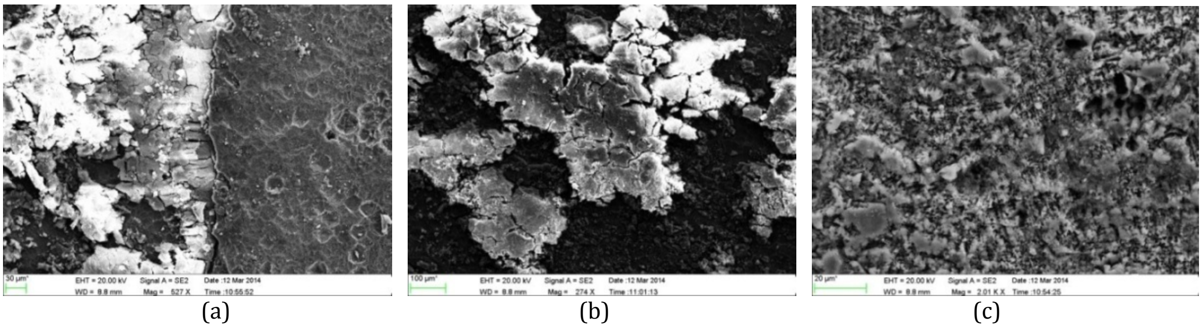

Fig. 5 SEM images of sample A with FSW joint with parameters axial load 10 kN, rotational speed 400 rpm and transverse speed 30 mm/min: (a) left side of nugget zone; (b) nugget zone; (c) right side of nugget zone

Fig. 5 shows the scanning electron microscopic images of sample A. It has three parts: (a) showing the left side of the weld zone, (b) showing the right side of the weld zone and (c) showing the centre of the weld zone. The sample A shows severe attack of the alkaline solution on the surface of the welded plate. The corrosion of the metal is found to have occurred in the welded zone. The oxides of metal are formed on the surface. Pitting corrosion is found to take place in the welded zone.

Fig. 6 shows the scanning electron microscopic images of sample B. It has three parts: (a) showing the left side of the weld zone, (b) showing the right side of the weld zone and (c) showing the centre of the weld zone. The alkaline solution, in which the welded plate was immersed, is found to have caused some effect on the surface. There are no severe traces of corrosion in sample B. The sample B shows considerable corrosion resistance.

Fig. 7 shows the scanning electron microscopic images of sample C. It has three parts: (a) showing the left side of the weld zone, (b) showing the right side of the weld zone and (c) showing the centre of the weld zone. The welded surface is found to be least attacked by the alkaline solution in sample C. There are traces of oxides present on the surface. It is not as severe in sample A.

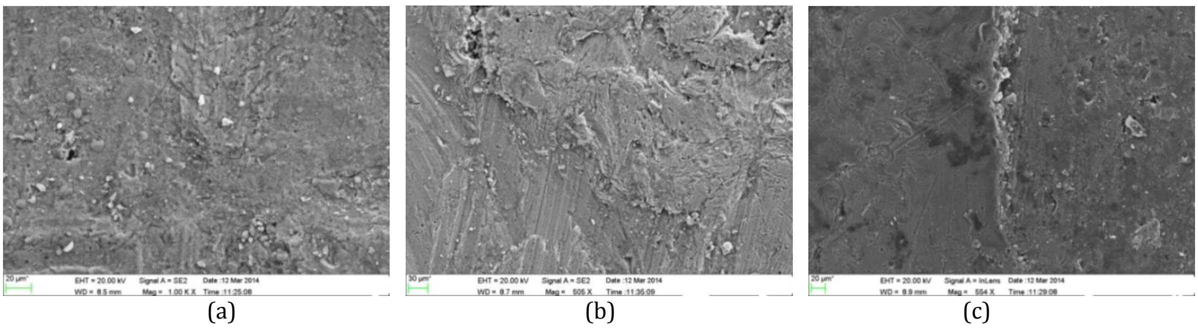

Fig. 6 SEM images of sample B with FSW joint with parameters axial load 12 kN, rotational speed 600 rpm and transverse speed 40 mm/min: (a) left side of nugget zone; (b) nugget zone; (c) right side of nugget zone

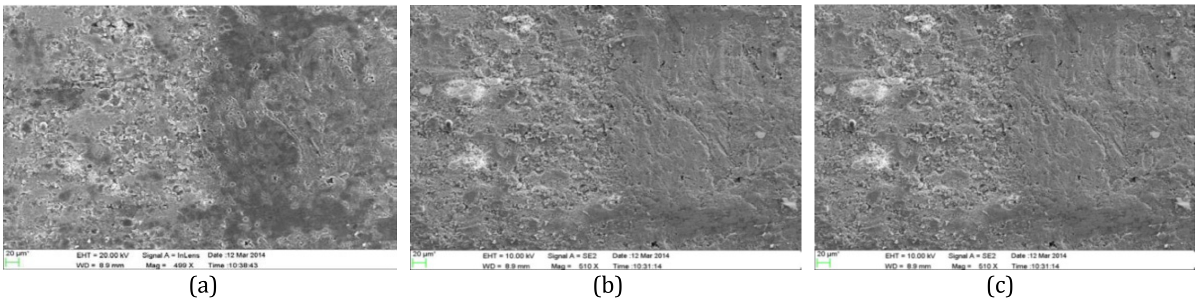

Fig. 7 SEM images of sample C with FSW joint with parameters axial load 16 kN, rotational speed 1200 rpm and transverse speed 50 mm/min: (a) left side of nugget zone; (b) nugget zone; (c) right side of nugget zone

4. Result and discussion

4.1 EDAX analysis of sample A

The EDAX image of sample A is shown in the Fig. 8. This shows the presence of oxides of aluminium alone. The spectrum shows that 23.56% of O and remaining Al are present. Thus, the welded zone is severely corroded. The pitting corrosion has occurred on the surface due to the effect of the alkaline solution.

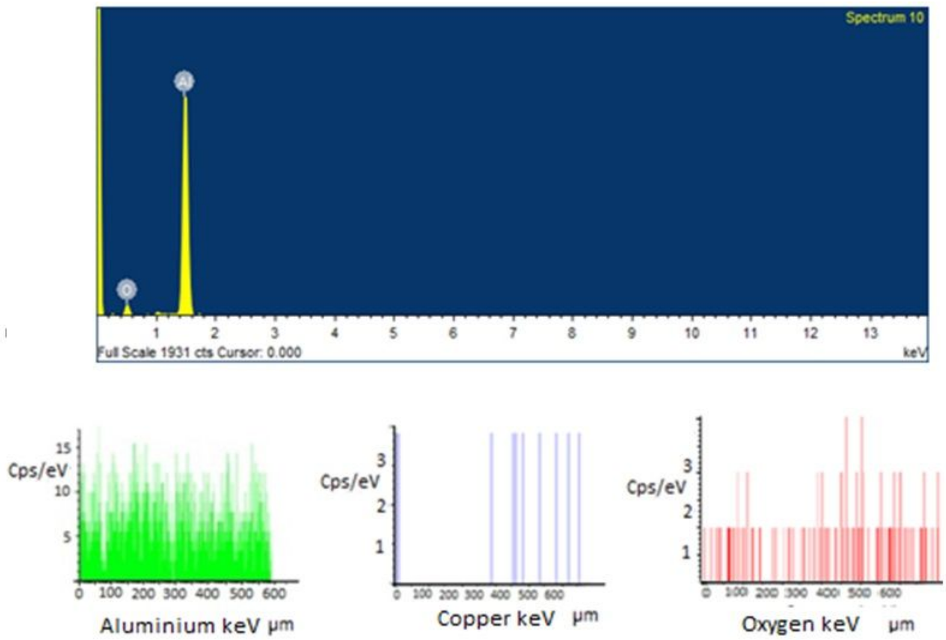

Fig. 8 EDAX images of sample A (FSW joint with parameters axial load 10 kN, rotational speed 400 rpm and transverse speed 30 mm/min)

4.2 EDAX analysis of sample B

The EDAX image of the sample B (Fig. 9) shows the presence of 28.34 % of O, 18.75 % of C, 5.20 % of Cu, 1.29 % of Mg, 1.21 % of Si, 1.12 % of Na, 0.86 % of Fe, 0.71 % of Mn, 0.50 % of Cl, 0.42 % of Ca and remaining Al by weight. This shows that the percentage composition by weight of sample B shows small deviation from that before corrosion.

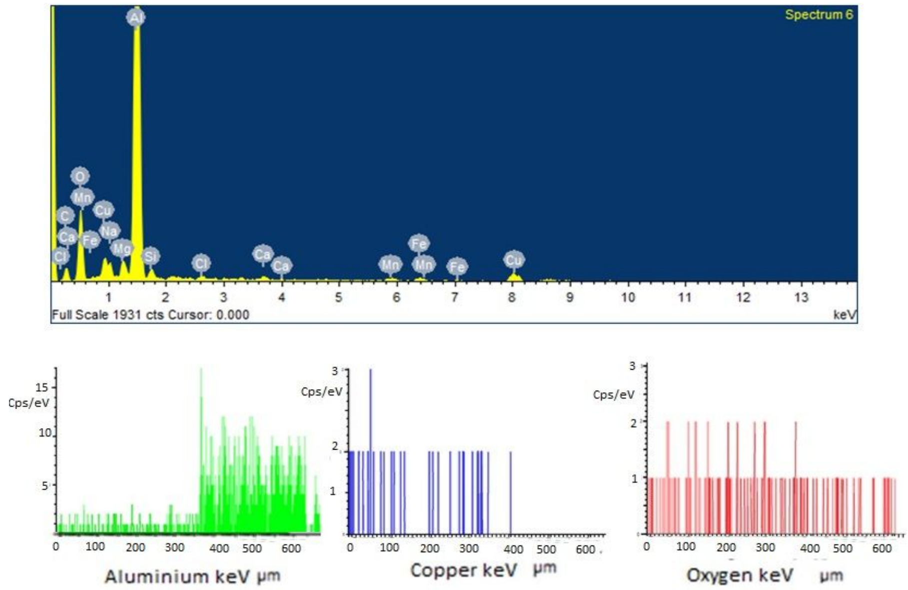

Fig. 9 EDAX images of sample B (FSW joint with parameters axial load 12 kN, rotational speed 600 rpm and transverse speed 40 mm/min)

4.3 EDAX analysis of sample C

The EDAX of sample C (Figure 10) shows the presence of 28.92 % of O, 16.52 % of C, 3.51 % of C, 0.96 % of Fe, 0.82 % of Si, 0.74 % of Mg, 0.42 % of Ca and remaining Al by weight. This shows that the composition percentage by weight of the corroded region shows slight variation from parent metal composition.

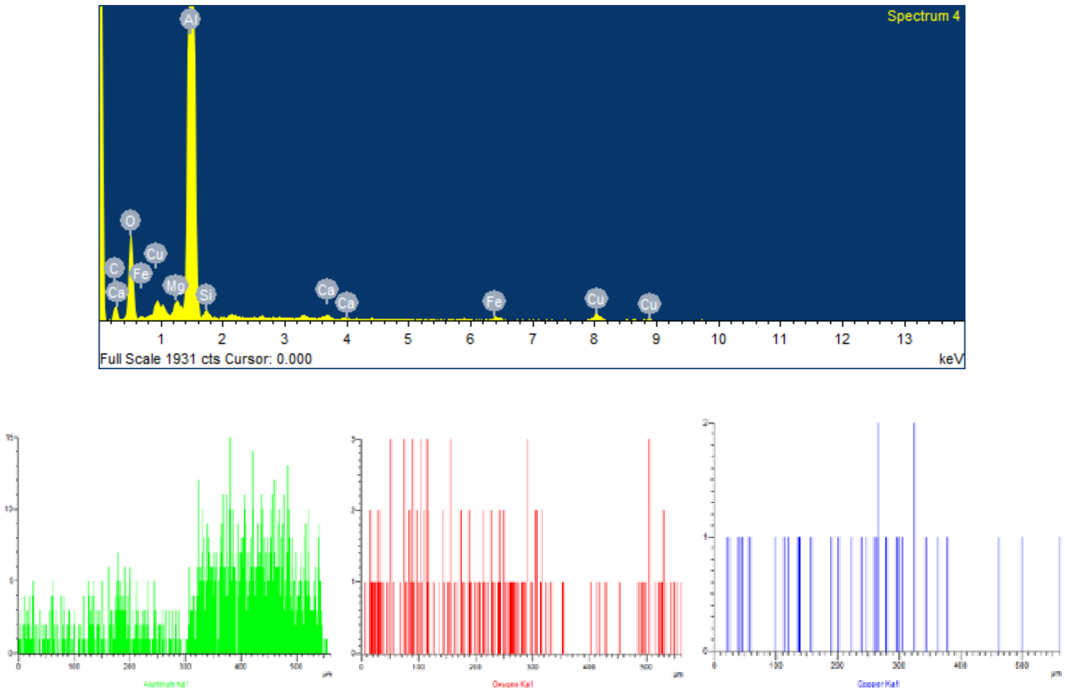

Fig. 10 EDAX images of sample C (FSW joint with parameters axial load 16 kN, rotational speed 1200 rpm and transverse speed 50 mm/min)

Thus upon experimental analysis, followed by imaging of the specimen with Scanning Electron Microscope, to study the microstructure, and the Energy Dispersive X-ray Analysis of the specimen, to study the composition, showed that two out of three specimen were much resistant to corrosion than the third specimen. The specimen B with weld parameters 12 kN, 600 rpm and

40 mm/min and the specimen C with weld parameters 16 kN, 1200 rpm and 40 mm/min are suitable for application. The specimen A with weld parameters 10 kN, 400 rpm and 30 mm/min is susceptible to corrosion. So it is not suitable for application in highly corrosive environments such as seawater.

5. Conclusion

The aluminium and magnesium alloys have a wide range of application such household utensils, construction equipment, packaging, vessels used in industries, pipes, aircrafts, ships, marine equipment, weapons, etc. They are mainly used for their corrosion resistance property. High strength alloys of aluminium and magnesium alloys are used in aircrafts and ships. They can be welded easily only by using friction stir welding technique. Therefore, care has to be taken that there is no probability of corrosion in the welded region. This work reveals that the so called non-corrosive alloys of aluminium and magnesium are also affected by the universal process of corrosion. But it can be reduced by using the optimum parameters of the weld. Welding can take place at any set of parameters, but a safe set of parameters to weld, which will prevent the welded zone from corrosion should be chosen. According to this investigation, it is concluded that welded region is susceptible for corrosion when the axial load and the rotational speed are kept low. As the value of these parameters increased the welding is done more and more perfectly. Out of the three sets of parameters the welded sample C shows more corrosion resistance than the other two sets of parameters. So we conclude that welding the alloy plates of AA 6061 and AZ 61 at 16 kN axial load, 1600 rpm rotational speed and 50 mm/min weld speed is most suitable.

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APEM journal

Advances in Production Engineering & Management
Volume 11 | Number 3 | September 2016 | pp 192–206
http://dx.doi.org/10.14743/apem2016.3.220

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Scheduling batches in multi hybrid cell manufacturing system considering worker resources: A case study from pipeline industry

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A B S T R A C T

This study considers batch scheduling problem in the multi hybrid cell manufacturing system (MHCMS) taking into account worker resources. This problem consists of determining sequence of batches, finding the starting time of each batch, and assigning workers to the batches in accordance with some pre-determined objectives. Due to a lack of studies on the batch scheduling problem in the MHCMS, a binary integer linear goal programming mathematical model is developed for bi-objective batch scheduling problem in this study. The formulated model is difficult to solve for large sized problem instances. To solve the model, we develop an efficient heuristic method called the Hybrid Cells Batch Scheduling (HCBS) heuristic. The proposed HCBS heuristic permits integrating batch scheduling and employee (worker) timetabling. Furthermore, we construct upper and lower bounds for the average flow time and the total number of workers. For evaluation of the performance of the heuristic, computational experiments are performed on generated test instances based on real production data. Results of the experiments show that the suggested heuristic method is capable of solving large sized problem instances in a reasonable amount of CPU time.

A R T I C L E I N F O

Keywords:
Batch scheduling
Hybrid manufacturing cells
Hybrid cells batch scheduling
Goal programming
Heuristic
HCBS heuristic

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Article history:
Received 24 June 2016
Revised 14 August 2016
Accepted 24 August 2016

1. Introduction

Cellular manufacturing (CM), described as the applications of the group technology principles in a manufacturing environment, is a production system in which the parts with similar processing requirements and machines are grouped in distinct manufacturing cells [1, 2]. The main advantages offered by CM are reduction in setup time, reduction in lead time, reduction in work-in-process inventory, enhanced visibility and quality, efficient material handling, simplified scheduling and production control, and an increase in flexibility [3, 4-7].

The problems in a CMS are classified mainly into design and operational aspects. Design problems contain formation of cells and layout planning of cells while operational problems involve assignment of workers (employees) and scheduling of parts/batches-groups into the cells [1]. Operational problems have not been considered extensively in the extant literature compared to design problems [8]. This paper considers the problem of batch scheduling in the MHCMS which is a type of CMS consisting of a number of parallel independent hybrid cells. Most of the real CMSs are composed of hybrid cells, and both automatic and manual operations are performed in these cells [9]. The importance of the worker assignment on batch scheduling problems comes to light more clearly especially in the hybrid cells. Worker involvement is not bounded in these cells and the number of workers in cells plays an important role and directly affects the cell cycle times. Due to the manual operations within the hybrid cells, cell cycle times vary from high to low and the flow times of the batches depend on the number of workers assigned to work on these batches. Therefore, the decisions must be made simultaneously for the batch scheduling problem in the MHCMS are the sequence of batches on each cell, the starting time of each batch and the workers assigned to operations of batches on cells.

In the current study, scheduling in multi hybrid manufacturing cells, which are arranged as flowline, is addressed. A goal-programming model has been developed for scheduling of batches within cells by considering worker resource. Two conflicting objectives are identified for the problem: minimization of the average flow time and minimization of the total number of workers in the system. Since the average flow time can be used as a performance indicator for resource utilization [10], it is determined as one of the conflicting objectives in this study. To the best of our knowledge, the batch scheduling problem for the MHCMS is examined here for the first time.

Due to the computational complexities, it is fairly challenging to obtain optimal solutions to scheduling problems in real sized problem instances with exact optimization methods [11]. As such, a heuristic method, namely the HCBS heuristic, is developed for this problem. Computational results show that the heuristic method presented in the paper has the capability of solving large sized problem instances with industrial pertinence efficiently. The motivation of this study is the batch scheduling problem arising in a real life CMS. Therefore, the study has the ability of adding value to industry in the way of effectively raising engineering control for scheduling activities in CMSs. In this context, the aim of the study is to propose a new batch scheduling method for multi hybrid cell manufacturing system under resource constraints and to verify this method on an industrial application. Furthermore, this study has the originality of proposing a novel goal programming model and a heuristic method via the parallel consideration of the total number of workers and the average flow time in the MHCMS.

The flow of this study is as follows: review of the relevant literature is included in Section 2. Problem definition, mathematical model and a numerical example are presented and explained in Section 3. The developed heuristic method is introduced in Section 4. The experimental data and the computational results of the proposed heuristic method are reported in Section 5. The conclusions and recommendations for future research are offered in Section 6.

2. Literature review

In this study, batch scheduling problem in the MHCMS is investigated by considering worker resource. Therefore, the literature is reviewed two headlines as the worker assignment and allocation problems in the CMS and the batch scheduling problem in multi cell manufacturing system.

Jensen [12] used the simulation method to examine performance advantages of labor flexibility for departmens, hybrid cells and strict cells. Askin and Huang [13] proposed a multi-objective model to improve the fitness of individual workers to tasks performed in cells, and to create effective teams. Norman et al. [14] examined the problem of allocating workers to cells to improve organizational effectiveness which is affected by productivity, quality and training cost. Süer and Dagli [15] examined cell loading and labor allocation problems. They created a three-stage structure and examined solutions to sequencing, labor allocation and cell loading problems. Cesani and Steudel [16] used the simulation method to investigate the effects of varied labor allocation policies on system performance. Their results show that balance in the number of workers is a significant determinant of system performance. Süer and Tummaluri [7] studied the problem of assigning operators to operations in labor intensive cells. They proposed a three-stage approach for the solution of the problem. Fowler et al. [17] examined differences between workers, in terms of their general cognitive ability (GCA), and developed a mathematical model to minimize worker-related costs over multiple periods. Davis et al. [18] used the simulation method to examine the relationship between cross training and workload imbalance, and found that workload imbalance increased the need for worker flexibility. Fan et al. [19] examined multi-objective cell formation and operator assignment problems. Süer and Alhawari [20] examined the use of two different operator assignment strategies (Max-Min and Max) in labor intensive manufacturing cells. Azadeh et al. [21] examined the problem of operator allocation in a CMS by combining fuzzy data envelopment analysis (FDEA) and fuzzy simulation techniques. Egilmez et al. [22] examined the problem of stochastic skill-based workforce assignment in a CMS where both operation times and demand are uncertain. Niakan et al. [23] developed a new bi-objective model of the cell formation problem to handle worker assignment and environmental and social criteria. Liu et al. [24] developed a decision model for employee assignment and production control in a CMS with considering learning and forgetting effects of employees.

As the body of the literature addressing the worker assignment and allocation problems in the CMS ruled out up to the present the effect of number of workers on the flow time of batches on the cells, the present study moves in that direction.

Batch scheduling problem in CMS is also addressed in this study. Little research has been conducted on batch scheduling problem in multi-cell manufacturing system in the literature. The following is a review of studies that examine the batch scheduling problem in multi-cell manufacturing system.

Das and Canel [25] proposed a branch and bound solution method to seek solution to the problem of scheduling of batches in the multi-cell flexible manufacturing system (MCFMS). Celano et al. [26] used simulation method to analyze the batch scheduling problem within a manufacturing system consisting of multiple cells. Hachicha et al. [2] utilized simulation method to design a CMS consisting of multiple cells in which parts are produced in batches. Balaji and Porselvi [27] proposed a model for batch scheduling problem in a MCFMS having sequence dependent batch setup time with flowline structure.

When considering the large body of the extant literature, it is revealed that there have been studies in the literature that focus on the batch scheduling problem in CMSs having multi cells. However, there has not been any published study addressing the influence of assignment of workers on flow times of batches for the batch scheduling problem in the CMSs. This problem has been observed in a real cellular manufacturing system in the pipeline industry and it has not been addressed in the literature before. This study bridges this gap in the literature.

3. Descriptions of the problem and mathematical model

3.1 Description of the problem

In the current study, the batch scheduling problem in the hybrid cells having missing operations (some parts may skip some operations on some machines) is examined. The distinctive feature of this problem is the dependence of the batch flow times on the number of workers assigned to the main operations of batches on cells.

The hybrid cells need attendance of workers constantly. Because of the presence of manual operations, changing the number of workers assigned to the operations in this type of manufacturing cells causes changes in cell cycle times, which in turn changes flow times of batches on cells. An increment in the number of workers in cells results in a decreases in flow times of batches, and vice versa. For this reason, determination of number of workers, which are assigned to cells to perform operations of batches, is important in the hybrid cell scheduling studies. Therefore, when seeking solutions to the batch scheduling problem in a CMS which consists of parallel hybrid cells, it is necessary to consider the sequence of batches, the starting times of batches and the worker assignment to the batches.

There are K unrelated parallel labour-intensive hybrid cells in the CMS. The hybrid cells consist of M machines, designed as flowlines, dedicated to process I batches. The assumptions which have been made in the study are as follows:

- The cell compositions and the assignment of batches to cells are known in advance.
- Each machine in a cell corresponds to an operation, and these operations combine to form main operation. Pre-emption of operations and main operations is not allowed.

- Parts are produced in batches, and one-piece flow is applied within the cells. The flow is uni-directional and no back-tracking is allowed.
- Batches are processed from only one family in each cell and at most one batch can be processed in a cell at the same time.
- The batch sizes are equal to order sizes and batch splitting is not permitted.
- Batches are available for processing at time zero and processing times include setup times.
- Each worker has same multi-skills to perform all operations on cells.

3.2 Mathematical model

In this section, to describe the problem more clearly, a binary integer linear goal programming mathematical model is developed to address conflicting objectives which are the total number of workers and the average flow time. The purpose of the proposed mathematical model is to contribute to the apperception of the scheduling problem addressed in the study.

The indices, parameters, variables, deviational variables, decision variables and mathematical models are introduced in this section.

Indices

i,j – Indices of batches (i,j = 1,…, N)
z – Index of workers (z = 1,…, Z)
m – Index of machines (m = 1,…, M)
k,t – Indices of cells (k,t = 1,…, K)

Parameters

w_1 – Weight of the first objective (average flow time)
w_2 – Weight of the second objective (total number of workers)
$ak_{i,k}$ – If batch i is allocated to cell k, 1; if not, 0
$avewalking_k$ – Average walking time of workers in cell k
$totalwalking_k$ – Total walking time of workers in cell
$using_{i,k,m}$ – If machine m is used for operation of batch i on cell k, 1; if not, 0
$manualpro_{i,k,m}$ – Manual processing time for parts in batch i on machine m in cell k
$autopro_{i,k,m}$ – Automatic processing time for parts in batch i on machine m in cell k
$pt_{i,k,m}$ – Processing time of parts in batch i on machine m in cell k
$lpt_{i,k}$ – Longest processing time for parts in batch i on cell k
$FLT_{i,k}$ – Completion time for the first part in the batch i on cell k
$cycmin_{i,k}$ – Minimum cell cycle time for batch i on cell k
$cycmax_{i,k}$ – Maximum cell cycle time for batch i on cell k
q_i – Number of parts in batch i

Variables

$f_{i,k}$ – Flow time of batch i on cell k
$c_{i,k}$ – Completion time of batch i on cell k
$cyc_{i,k}$ – Cell cycle time for batch i on cell k
$time_{j,t}$ – Starting time of batch j on cell t
$workforce_{j,t}$ – Total number of workers at the start of main operation of batch j on cell l
mw – Maximum number of workers in the system
$wo_{z,i,k,m}$ – If worker z is assigned to machine m for main operation of batch i on cell k, 1; if not, 0
$x_{i,k}$ – Number of workers assigned for batch i on cell k
$g_{i,k,j,t}$ – If main operation of batch i on cell k and the main operation of batch j on cell t overlap in time, 1; if not, 0

Deviational Variables

$d1$-$d2$ – Positive deviational variables for the average flow time and the total number of workers, respectively

Decision variables

$w1_{z,i,k}$ – If worker z is assigned to main operation of batch i on cell k, 1; if not, 0

$b_{i,j,k}$ – If batch i is processed after batch j on cell k, 1; if not, 0
(Note that after does not necessarily means immediately after)

The mathematical formulation of the binary integer linear goal programming model is as follows:

Objective Function

$$\min objective = w1 \times (d1/(UP1 - LB1)) + w2 \times (d2/(UP2 - LB2)) \tag{1}$$

Constraints

$$\sum_{k=1}^{K}(maxc_k/maxc_k) - d1 = LB1 \tag{2}$$

$$mw - d2 = LB2 \tag{3}$$

$$c_{i,k} \geq (c_{j,k} + f_{i,k}) - M \times (1 - b_{i,j,k}) \qquad \forall i,j,k \tag{4}$$

$$c_{i,k} \geq f_{i,k} \qquad \forall i,k \tag{5}$$

$$maxc_k \geq c_{i,k} \qquad \forall i,k \tag{6}$$

$$b_{i,j,k} + b_{j,i,k} = ak_{i,k} \times ak_{j,k} \qquad \forall i,j,k \quad i \neq j \tag{7}$$

$$time_{j,t} = c_{j,t} - f_{j,t} \qquad \forall j,t \tag{8}$$

$$(c_{i,k} - f_{i,k}) - time_{j,t} \leq M \times (1 - ka_{i,k,j,t}) \qquad \forall i,k,j,t \tag{9}$$

$$time_{j,t} - (c_{i,k} - f_{i,k}) \leq M \times ka_{i,k,j,t} \qquad \forall i,k,j,t \tag{10}$$

$$time_{j,t} - c_{i,k} \leq M \times (1 - kb_{i,k,j,t}) \qquad \forall i,k,j,t \tag{11}$$

$$c_{i,k} - time_{j,t} \leq M \times kb_{i,k,j,t} \qquad \forall i,k,j,t \tag{12}$$

$$2 - (ka_{i,k,j,t} - kb_{i,k,j,t}) \leq M \times (1 - g_{i,k,j,t}) \qquad \forall i,k,j,t \tag{13}$$

$$(ka_{i,k,j,t} - kb_{i,k,j,t}) - 1 \leq M \times g_{i,k,j,t} \qquad \forall i,k,j,t \tag{14}$$

$$f_{i,k} = cyc_{i,k} \times (q_i - 1) + FLT_{i,k} \qquad \forall i,k \tag{15}$$

$$cycmin_{i,k} \leq cyc_{i,k} \qquad \forall i,k \tag{16}$$

$$\sum_{m=1}^{M} w_{z,i,k,m} \times (avewalking_k + manualpro_{i,k,m}) \leq cyc_{i,k} \qquad \forall i,k,z \tag{17}$$

$$\sum_{z=1}^{Z} w_{z,i,k,m} = using_{i,k,m} \qquad \forall i,k,m \tag{18}$$

$$\sum_{m=1}^{M} w_{z,i,k,m} \leq w1_{z,i,k} \times M \qquad \forall z,i,k \tag{19}$$

$$(w1_{z,i,k} + w1_{z,j,t}) - 1 \leq M \times (1 - g_{i,k,j,t}) \qquad \forall z,i,k,j,t \quad i \neq j, k \neq t \tag{20}$$

$$x_{i,k} = \sum_{z=1}^{Z} w1_{z,i,k} \qquad \forall i,k \tag{21}$$

$$x_{i,k} - y_{i,k,j,t} \leq M \times (1 - g_{i,k,j,t}) \qquad \forall i,k,j,t \tag{22}$$

$$y_{i,k,j,t} \leq M \times g_{i,k,j,t} \qquad \forall i,k,j,t \tag{23}$$

$$workforce_{j,t} = \sum_{i=1}^{N}\sum_{k=1}^{K} y_{i,k,j,t} \qquad \forall j,t \tag{24}$$

$$mw \geq workload_{j,t} \qquad \forall j,t \tag{25}$$

$$b_{i,j,k}\ 0\ or\ 1\ ;\ x_{i,k}\ integer\ ;\ d1 \geq 0\ ;\ d2 \geq 0 \tag{26}$$

The objective function (Eq. 1) involves two terms, one for each of the conflicting objectives, and presents a weighted average of deviations from developed lower bounds. The first term minimizes the deviation of the average flow time from *LB1* (Eq. 32). The second term attempts to minimize the deviation of the total number of workers from *LB2* (Eq. 34), and is in conflict with the first term. In Eq. 1, a zero-one normalisation scheme is used to scale all unwanted positive deviations (*d1* and *d2*) onto a zero-one range [28]. Eq. 2 and Eq. 3 are soft constraints which represent positive deviations from target levels ($LB1$ and $LB2$) for the average flow time and the total number of workers objectives, respectively. Eq. 4 ensures that each cell can process at most one batch at the same time. Eq. 5 implies that the completion time of a batch is greater than or equal to the flow time of this batch. Eq. 6 implies that the total completion time in a cell (C_k) is greater than or equal to the largest completion times of batches in this cell. Eq. 7 ensures that if batches i and j are allocated to the cell k, then $b_{i,j,k}$ or $b_{j,i,k}$ gets value equal to one. Eq. 8 represents the time points ($time_{j,t}$) at which the total number of workers can change, that is to say, the starting times of the main operations. Eqs. 9-14 are used to determine main operations which coincide with the time points ($time_{j,t}$) . Eq. 15 is used to calculate the flow times of the batches. Eq. 16 and Eq. 17 are used to determine the cell cycle time for each batch. Eq. 18 is used to assign workers to machines where the operations are performed. Eq. 19 ensures that worker assigned to machine for operation is also assigned to the cell that contains the machine in question. Eq. 20 prevents the assignment of the same worker to two main operations which overlap in time. Eq. 21 is used to calculate the number of workers assigned for operation of batch i on cell k. Eqs. 22-24 are used to calculate the total number of workers at each time point ($workforce_{j,t}$). Eq. 25 indicates that the total number of workers in the system is greater than or equal to the total number of workers at each time points. Eq. 26 is used for the binary, integer and sign bounds on the variables. The constant M in the equations should be sufficiently large. Since the mathematical model is developed considering the parallel cells in this study, the related studies involve parallel machine/cell scheduling problems and mathematical models constructed by Yang et al. [11] and Dalfard et al. [29] can be examined by interested readers to obtain comprehensive perspective. It is also important to emphasize that although Eqs. 17-19 are proposed to calculate the cell cycle times in case of dedicated assignment of workers to the hybrid cells. Eq. 27 is developed to obtain the cell cycle times. Since each worker has the same multi-skills in the MHCMS, theoretical values of the cell cycle times, which are the best values that can be reached, are calculated by using Eq. 27 and it is used in the solution of the model instead of Eqs. 17-19.

$$cyc_{i,k} = \left(cycmax_{i,k}/x_{i,k}\right) \qquad \forall i,k \tag{27}$$

The parameters $cycmax_{i,k}$ and $cycmin_{i,k}$ are calculated using Eq. 28 and Eq. 29, respectively.

$$cycmax_{i,k} = \sum_{m=1}^{M}(totalwalking_k + manualpro_{i,k,m}) \qquad \forall i,k \tag{28}$$

$$cycmin_{i,k} = lpt_{i,k} \qquad \forall i,k \tag{29}$$

The longest processing time for parts on a cell is equal to maximum of processing times of machines in this cell. This fact is stated in Eq. 30. The processing time for parts on each machine is equal to sum of manual processing time and automatic processing time. This fact is stated in Eq. 31.

$$lpt_{i,k} = \max_{\forall m}(pt_{i,k,m}) \qquad \forall i,k \tag{30}$$

$$pt_{i,k,m} = manualpro_{i,k,m} + autopro_{i,k,m} \qquad \forall i,k,m \tag{31}$$

In this paper, we put forward lower and upper bounds for the average flow time and the total number of workers. The derivation of lower bound ($LB1$) and upper bound ($UP1$) for average flow time are expressed as follows:

$$LB1 = \left(\sum_{k=1}^{K}\sum_{i=1}^{N}\left(cycmin_{i,k} \times (q_i - 1) + FLT_{i,k}\right)/K\right) \tag{32}$$

$$UP1 = \left(\sum_{k=1}^{K}\sum_{i=1}^{N}\left(cycmax_{i,k} \times (q_i - 1) + FLT_{i,k}\right)/K\right) \tag{33}$$

The derivation of lower bound ($LB2$) and upper bound ($UP2$) for the total number of workers are expressed as follows:

$$LB2 = \sum_{k=1}^{K}\left(\min_{\forall i}\left(cycmax_{i,k}/cycmax_{i,k}\right)\right) \tag{34}$$

$$UP2 = \sum_{k=1}^{K}\left(\max_{\forall i}\left(cycmax_{i,k}/cycmin_{i,k}\right)^{+}\right) \tag{35}$$

3.3 Numerical illustration

To explain the problem considered in this paper, we present a MHCMS with missing operations (MO). In this system, batches between 1 and 6 are to be scheduled in the first cell and batches between 7 and 12 are to be scheduled in the second cell. The maximum and minimum cell cycle times for each batch, the batch sizes, the automatic and the manual processing times of parts of batches on machines and the total walking time in cells are presented in Table 1. As seen in this table, the operations on machine 3 are missing operations for batch 1 to batch 6 and the operations on machine 2 are missing operations for the batch 7 to batch 12. There is a worker pool which is consists of five different workers. The mathematical model was coded in the GAMS CPLEX software package for equal weights of objectives ($w1$ = 0.5; $w2$ = 0.5). The optimal solution was derived in 676 min. of computational time. The results of the CPLEX software are reported below. Fig. 1 illustrates optimum solution of this problem. In Fig. 1, the best sequence of batches on Cell 1 and Cell 2 is obtained as 1-4-3-5-2-6 and 9-8-7-10-11-12, respectively. The starting and completion times of each batch are shown in Fig. 1. The average flow time is equal to 1800, the total number of workers is equal to 3 and the objective function is equal to 0.26.

Table 1 Data for a 12-batch 2-cell batch scheduling example

		Cell Cycle Times		Batch Size	Machine1		Machine2		Machine3		Machine4		Total Walking
		Max	Min		Aut.	Man.	Aut.	Man.	Aut.	Man.	Aut.	Man.	
Cell 1	Batch 1	60	30	5	5	15	0	10	MO	MO	10	20	15
	Batch 2	80	30	10	0	20	0	15	MO	MO	0	30	15
	Batch 3	55	30	5	10	10	0	15	MO	MO	15	15	15
	Batch 4	35	35	10	20	0	0	10	MO	MO	25	10	15
	Batch 5	50	30	5	5	5	0	10	MO	MO	10	20	15
	Batch 6	80	30	10	0	20	0	15	MO	MO	0	30	15
Cell 2	Batch 7	75	30	5	15	15	MO	MO	0	30	20	10	20
	Batch 8	50	20	10	10	10	MO	MO	0	20	20	0	20
	Batch 9	40	20	5	10	0	MO	MO	0	20	20	0	20
	Batch 10	30	30	10	10	0	MO	MO	10	10	30	0	20
	Batch 11	50	30	5	5	5	MO	MO	0	10	10	20	15
	Batch 12	80	30	10	0	20	MO	MO	0	15	0	30	15

As seen in the numerical example, the model is difficult to solve in an acceptable amount of time even for small-sized problem instances. As the size of the problem increases, the computational time to find the optimum solutions increases, so optimum solutions cannot be found in a reasonable time. Therefore, developing a heuristic method is plausible to obtain good solutions even for the large-sized problem instances in an acceptable amount of computational time.

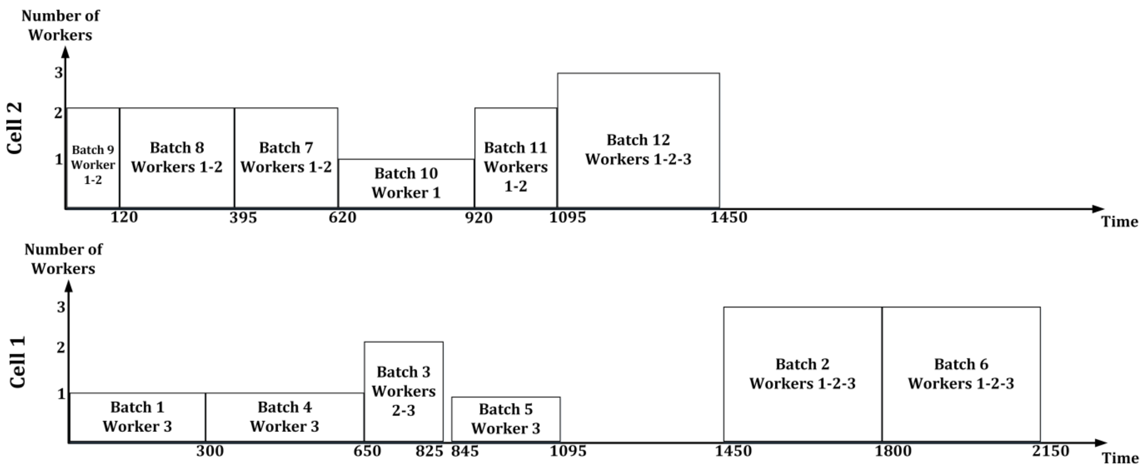


Fig. 1 Numerical example

4. A hybrid cells batch scheduling (HCBS) heuristic

The scheduling problems in CMS are evaluated as NP-hard and seeking the optimal solutions to these problems are computationally extensive [10, 27, 30-31]. Since the scheduling problems in CMS are regarded to be NP-hard, our problem is also NP-hard in the strong sense. Since it is hard to seek the solutions for this problem with exact methods, we developed a heuristic method to obtain near optimal solutions in a reasonable computational time. In order to analyse the effectiveness of our heuristic, we also constructed lower and upper bounds both for the average flow time and the total number of workers.

This section presents a heuristic method, namely the HCBS heuristic, for finding good solutions to the bi-objective batch scheduling problem with respect to the sequence of batches, starting times of batches and worker assignment to each batch.

The following terms and equations are used in the heuristic:

$ave.wor._{i,k}$ – Average number of worker for batch i on cell k

$$ave.wor._{i,k} = \left(\left(cycmax_{i,k}/cycmin_{i,k}\right)/2\right)^{+} \qquad \forall i,k \tag{36}$$

seq_k and $sequence_k$ – Sequence of batches on cell k
$sequence_{k,t}$ – Sequence of batches obtained at iteration r
$newx_{i,k}$ – Auxiliary variable for $x_{i,k}$

$$newx_{i,k} = x_{i,k} \pm 1 \qquad \forall i,k \tag{37}$$

$w1_{z,i,k,r}$ – If worker z is assigned to main operation of batch i on cell k at iteration r, 1; if not, 0
rn_k – Uniformly distributed random number for cell k
$newcyc_{i,k}$ – Auxiliary variable for $cyc_{i,k}$

$$newcyc_{i,k} = max\left(\left(cycmax_{i,k}/newx_{i,k}\right); cycmin_{i,k}\right) \qquad \forall i,k \tag{38}$$

$newp_{i,k}$ – Auxiliary variable for $f_{i,k}$

$$newf_{i,k} = newcyc_{i,k} \times (q_i - 1) + FLT_{i,k} \qquad \forall i,k \tag{39}$$

$dif_{i,k}$ – Difference between $f_{i,k}$ and $newf_{i,k}$

$$dif_{i,k} = \left|f_{i,k} - newf_{i,k}\right| \qquad \forall i,k \tag{40}$$

$alt_{i,k}$ – If the number of workers for batch i on cell k is increased or decreased, 1; if not, 0
$workerset_k$ – Set of workers for cell k
alt_k – Sum of the values of $alt_{i,k}$ for batch k

$$alt_k = \sum_{i=1}^{N} alt_{i,k} \qquad \forall k \tag{41}$$

$newobj_{i,j,k,t}$ – Auxiliary variable for *objective* in case of position of batch i and batch j is swapped and mode of starting time of batch i is equal to t in cell k
$starting_{i,j,k,t}$ – Possible starting time alternatives (modes) for batch i in case of position of batch i and batch j is swapped on cell k
$starting_{i,k,r}$ – Starting time of batch i on cell k at iteration r
$starting_{i,k}$ – Starting time of batch i on cell k
objective – Objective function value (Eq. 1)
$objective_t$ – Objective function value obtained at iteration t

As stated earlier, the HCBS heuristic is developed to determine the sequence of batches and the number of workers for each batch by minimising the weighted average of deviations of the average flow time and the total number of workers from lower bounds. The flowchart of the HCBS heuristic is given in Fig. 2.

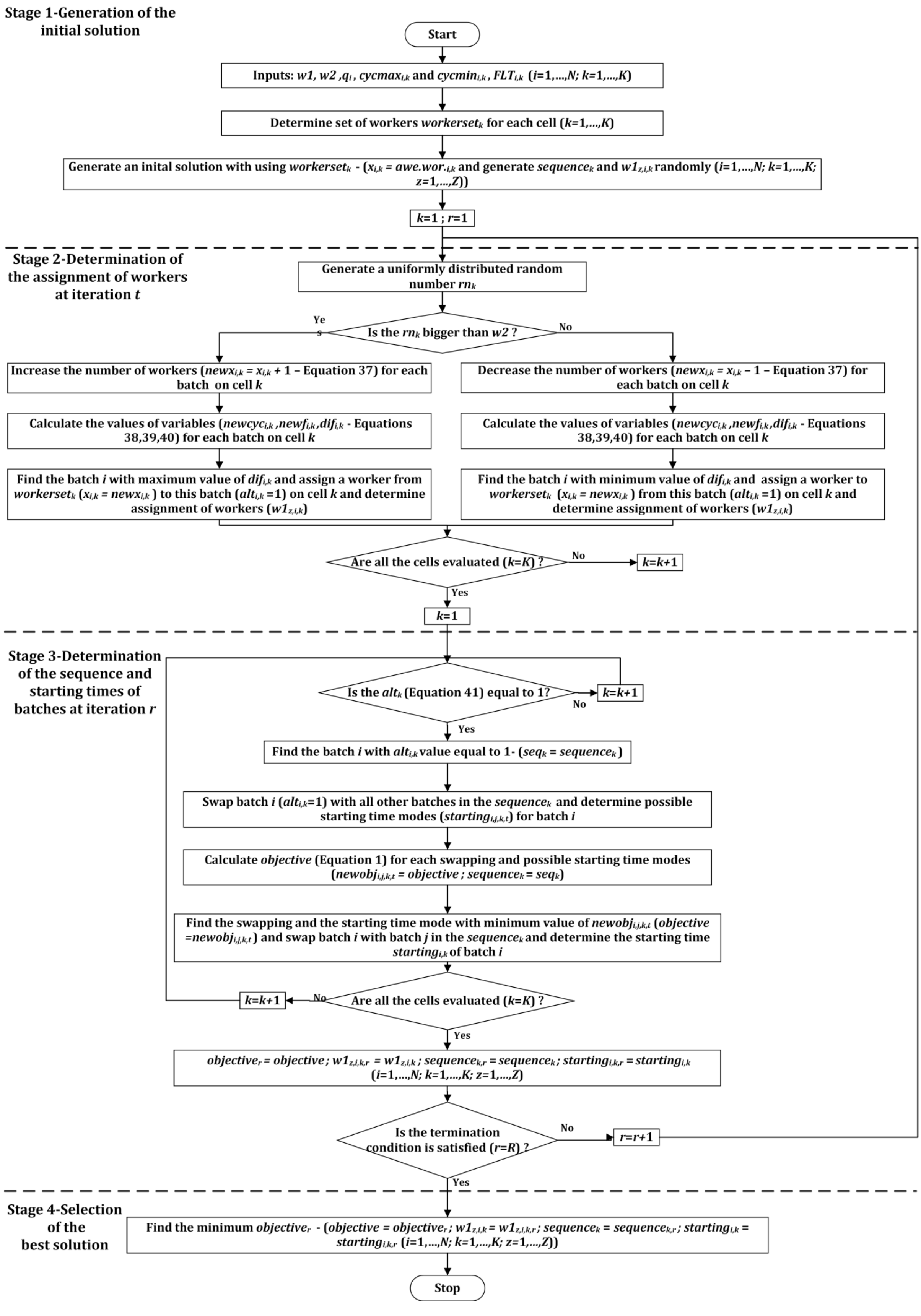


Fig. 2 The flowchart of HCBS heuristic

The input data for the HCBS heuristic is: the weights *w1* and *w2* of the objectives, the size q_i of batch *i*, the maximum and minimum cell cycle times, namely $cycmax_{i,k}$ and $cycmin_{i,k}$, for batch *i* on cell *k,* and the completion time $FLT_{i,k}$ for the first part in the batch *i* on cell *k*. The heuristic gives output such as the sequence of batches on each cell *k*, namely $sequence_k$, the starting time of batch *i* on cell *k*, namely $starting_{i,k}$, the assignment of workers to each batch, namely $w1_{z,i,k,r}$, and the *objective* (Eq. 1) .

The HCBS heuristic consist of four stages: (1) Generation of the initial solution; (2) determination of the assignment of workers for each batch at iteration *r* ; (3) determination of the sequence and starting times of batches for each cell at iteration *r* ; (4) selection of the best solution.

The first is related with the generation of the initial solution. This is provided by creating $workerset_k$ for each cell and assigning $ave.wor._{i,k}$ workers (Eq. 36) from $workerset_k$ for each batch on each cell. In this manner, assignment of the same worker to two or more main operations overlap in time is prevented. Sequences of batches on cells are first randomly generated. Then, Stage 2 and Stage 3 are executed for each iteration until the termination condition is satisfied. Stage 2 begins with evaluating the alternative scenarios of increasing or decreasing the number of worker for the first cell. In the following step, the effect of increase/decrease in the number of workers on flow time is computed for each batch (Eq. 40). Then, the decision about the change in number of workers is made with respect to pre-computed effect values. The $workerset_k$ is used when the number of workers assigned to the batch is changed. Then, Stage 2 is repeated for the following cells. Stage 3 of the heuristic tries each of the possible pairwise swaps and starting time modes $starting_{i,j,k,t}$ between the batch where the change in the number of workers is made in the previous stage and the other batches in the first cell. The heuristic generates starting time alternatives (modes) by means of allowing waiting times for batches so as to provide trade-off between number of workers and flow time. Waiting times are computed by considering the finishing time of current batches in other cells. The swap and starting time mode which yield the highest improvement in the objective function (Eq. 1) is executed. Consequently, the solution and objective function value for the iteration are recorded. Similar to Stage 2, Stage 3 scans each of the following cells respectively. Meanwhile, cells where the number of workers does not change in Stage 2 are excluded for swap operations. When the termination condition is met, the heuristic records the best solution through iterations as the final solution in Stage 4.

Table 2 Cell cycle times, batch sizes, processing time and total walking time

			Cell cycle times		Batch size	Processing time (s/unit) – $pt_{i,k,m}$								
			Max	Min		Roller	TIG Welding	Horizontal forming		Vertical forming	Reel	Cutting	Closing	Total walking time
Cells	Number of batches (NB)		($cycmax_{i,k}$)	($cycmin_{i,k}$)	(BS)	Manual	Manual	Manual	Automatic	Manual	Manual	Manual	Manual	($totalwalking_k$)
Cell 1	DN 25	1-Floating flange	957	450	5	16	150	MO	MO	450	155	108	62	16
		2-Fixed flange	622	468	4	16	150	110	358	MO	160	108	62	16
	DN 32	3-Floating flange	915	432	10	15	144	MO	MO	432	148	105	55	16
		4-Fixed flange	590	455	5	15	144	100	355	MO	152	105	58	16
	DN 40	5-Floating flange	887	420	15	15	140	MO	MO	420	145	96	55	16
		6-Fixed flange	555	438	8	15	140	88	350	MO	145	96	55	16
	DN 50	7-Floating flange	741	319	15	12	135	MO	MO	319	130	84	45	16
		8-Fixed flange	508	355	5	12	135	75	280	MO	138	84	48	16
Cell 2	DN 65	9-Floating flange	626	250	10	9	120	MO	MO	250	117	71	44	15
		10-Fixed flange	436	272	10	9	120	60	212	MO	117	71	44	15
	DN 80	11-Floating flange	472	155	15	8	108	MO	MO	155	88	66	32	15
		12-Fixed flange	363	186	9	8	108	26	160	MO	102	66	38	15
Cell 3	DN 100	13-Floating flange	525	182	12	8	115	MO	MO	182	95	71	40	14
		14-Fixed flange	414	210	8	8	115	50	160	MO	112	71	44	14
	DN 125	15-Floating flange	617	226	14	11	131	MO	MO	226	102	85	48	14
		16-Fixed flange	469	258	8	11	131	58	200	MO	120	85	50	14
	DN 150	17-Floating flange	755	318	10	14	145	MO	MO	318	115	94	55	14
		18-Fixed flange	541	360	5	14	145	80	280	MO	134	94	60	14
Cell 4	DN 200	19-Floating flange	940	431	5	18	153	MO	MO	431	139	118	65	16
		20-Fixed flange	653	490	15	18	153	120	370	MO	155	118	73	16
	DN 250	21-Floating flange	1070	485	10	25	168	MO	MO	485	163	135	78	16
		22-Fixed flange	739	545	8	25	168	135	410	MO	175	135	85	16
	DN 300	23-Floating flange	1202	528	10	34	185	MO	MO	528	188	161	90	16
		24-Fixed flange	857	607	5	34	185	147	460	MO	211	161	103	16

5. Computational experiments

In this section, a set of instances was generated based on the original production data obtained by a manufacturing company in the pipeline industry for performance evaluation of the HCBS heuristic. The focused company produces many types of expansion joints, and also fills custom orders. The present study examines the producing of axial metal bellowed expansion joint parts. These parts are divided into two main categories of fixed and floating flange joints.

The manufacturing system of the company consists of four parallel hybrid manufacturing cells and a functional layout. In this study, functional layout was not taken into consideration. Part families produced in the cells differ by their nominal diameters. There are four part families with different diameters. These are part families with nominal diameters DN 25-32-40-50, DN 65-80, DN 100-125-150 and DN 200-250-300. There are seven different types of machines in the cells: roller, TIG welding, horizontal forming, vertical forming, reel, cutting and closing machines. The minimum and the maximum cell cycle times for the batches, the size of the batches and the processing time of machines are given in Table 2. The missing operations are represented as MO in Table 2.

The heuristic was coded in MATLAB software and tested on the same computer, a 2.4 GHz Intel(R) Core™ i7-3630QM CPU with 16 GB of RAM.

5.1 Experimental data

Since there are no benchmark instances which consider batch scheduling problems in the MHCMS, problem instances were generated via experimental design based on real production data in Table 2. The experimental factors and their levels are presented in Table 3. Moreover coefficients for objective function is evaluated under three combinations, namely labour dominant (w_1 = 0.2; w_2 = 0.8), equally weighted (w_1 = 0.5; w_2 = 0.5) and flow time dominant (w_1 = 0.8; w_2 = 0.2). A total of 3×3×3×3 = 81 test problems are generated and solved for each of the combinations of the weights. Each experiment is repeated ten times. Hence, the number of runs in the experimentation amounted to 2430 (81×3×10). After a series of repetitive experiments, 50-iteration is found to be appropriate as termination condition for HCBS heuristic.

The performance of heuristic is evaluated in terms of the objective function value, the total number of workers, the average flow time and the CPU time. Note that deviation from LB for objective function has the same numerical value with objective function itself since the related LB is zero.

Table 3 The experimental factors and their levels

	Levels		
Number of batches on each cell (NBEC)	Low $[0,7\times NB]^+$	Medium [NB]	High $[1,5\times NB]^+$
Batch size on each cell (BSEC)	Low $[0,7\times BS]^+$	Medium [BS]	High $[1,5\times BS]^+$
Processing time (MPT)	Low $[0,7\times pt_{i,k,m}]$	Medium $[pt_{i,k,m}]$	High $[1,3\times pt_{i,k,m}]$
Total walking time in each cell (TWEC)	Low $[0,7\times totalwalking_k]$	Medium $[totalwalking_k]$	High $[1,3\times totalwalking_k]$

5.2 Results and discussions

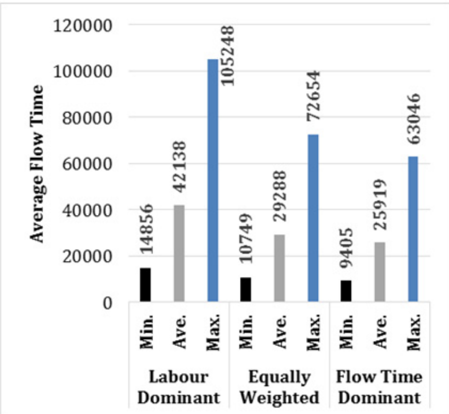
As can be understood from Table 4, the HCBS heuristic yielded satisfactory results with respect to deviation from lower bounds. Best objective function values are reached under flow time dominant configuration. When computation time is considered, it is concluded that the proposed heuristic has the capability of solving test problems efficiently (maximum = 23.63 s).

Table 4 Results under different objective function coefficient configurations

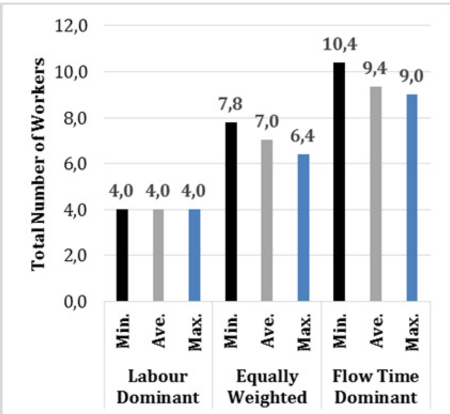
		Labour dominant	Equally weighted	Flow time dominant
Deviation from LB for objective function	Average	0.15	0.25	0.12
	Maximum	0.16	0.26	0.14
	Minimum	0.14	0.23	0.11
CPU time (s.)	Average	7.25	11.59	7.12
	Maximum	13.25	23.63	12.14
	Minimum	3.94	5.44	3.90

In addition, results of Fig. 3 indicated the sensitivity of average flow time and total number of workers performance to objective function configurations. It can be seen from Fig. 3(b), the maximum, the minimum and the average values of the number of workers are equal under labour dominant configuration. For the other configurations, changes in these values are low compare with values of average flow time in Fig. 3(a). The reason for this fact is that the total number of workers has not shown high sensitivity to different objective function coefficient combinations. The mathematical formulation of the total number of workers limits its sensitivity level. Hence, a new formulation related with the total number of workers can be developed to enhance the sensitivity level.

Furthermore, MANOVA is conducted to analyse the effect on the independent variables of NBEC, BSEC, MPT and TWEC (sources of variations) on the dependent variables of average flow time (AFT) and total number of workers (TNW). Statistical analysis is executed at 5 % significance level via SPSS 13.0 software. Note that, results for only equally weighted configuration is included to the analysis where main effects are investigated. According to the results, the effect of NBEC on the average flow time (p = 0.000) and the total number of workers (p = 0.001) are found to be statistically significant. In addition, BSEC (p=0.000) and MPT (p = 0.000) have significant effects on the average flow time. However, these factors do not have statistically significant effect on the total number of workers (p = 0.576 and p = 0.393, respectively). TWEC has been dominated by other factors with respect to their effects (p = 0.958 for AFT and p = 0.784 for TNW). Although NBEC, BSEC and MPT have a statistically significant effect on at least one dependent variable, TWEC has not a statistically significant effect on any dependent variables. BSEC and NBEC can be considered as the most influential factors on the average flow time and the total number of workers, respectively. With this information, it is concluded that the inputs related with batches, such as BSEC and NBEC, have a strong effect on the performance of the HCBS heuristic (R Squared = 0.930 and Adjusted R Squared = 0.922 for AFT; R Squared = 0.714 and Adjusted R Squared = 0.706 for TNW). It is also concluded that the factors are sufficient to explain significant percentage of variability in both AFT and TNW. Therefore, the independent variables determined in this study can be evaluated as the main factors which affect the operational efficiency in the MHCMS.

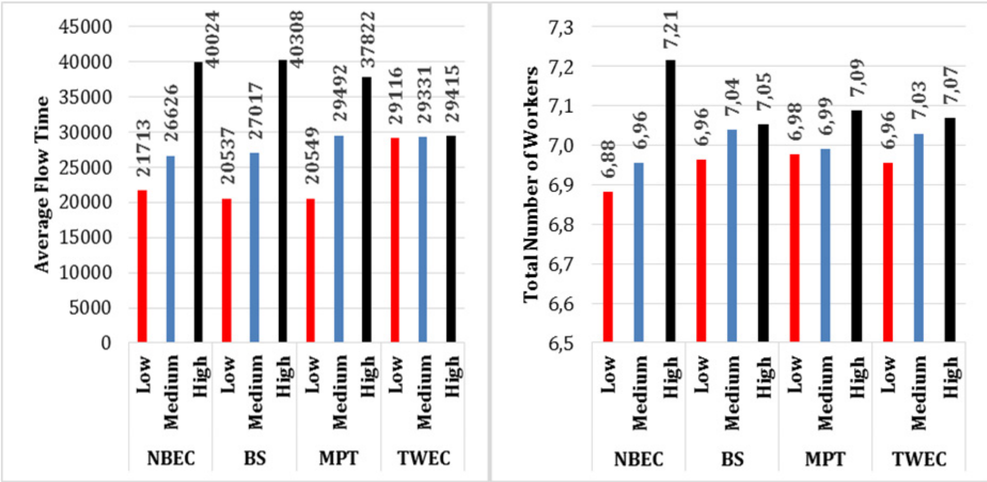


(a)



(b)

Fig. 3 Results for average flow time (a), and total number of workers (b)



(a) (b)

Fig. 4 Results for average flow time (a), and total number of workers (b)

The average flow time and the total number of workers for different levels of factors are provided in Fig. 4. According to this figure, the average flow time is crucially increasing with the rising level of the NBEC, BSEC and MPT. The observed trend of TWEC can be regarded as consistent with Table 4. The average flow time reaches its maximum value when the level of BSEC is high and its minimum value when the level of BSEC is low. Also, the total number of workers reaches its maximum value when the level of NBEC is high and its minimum value when the level of NBEC is low. As far as the total number of workers is concerned, slight differences among different levels have been observed for each factor. The results also show a non-monotonic trend of BSEC, MPT and TWEC in respect of the total number of workers. The reason for the small changes in total number of workers along with different levels of factors is that the sensitivity of the total number of workers to different level of factors is quite low compared to sensitivity of average flow time. As mentioned before, a new mathematical formulation can be developed and used in the method to increase the sensitivity level of the total number of workers to the factor levels.

Table 5 Multiple comparisons among factor levels

Factor	Dep. var.	I	J	Mean difference (I-J)	Sig. (*p*)	Factor	Dep. var.	I	J	Mean difference (I-J)	Sig. (*p*)
NBEC	AFT	Low	Medium	-4413.296*	0.000	MPT	AFT	Low	Medium	-8943.148*	0.000
			High	-18311.111*	0.000				High	-17272.704*	0.000
		Medium	High	-13897.815*	0.000			Medium	High	-8329.556*	0.000
	TNW	Low	Medium	-0.074	0.415		TNW	Low	Medium	0.007	0.935
			High	-0.333*	0.000				High	-0.104	0.255
		Medium	High	-0.259*	0.005			Medium	High	-0.111	0.223
BSEC	AFT	Low	Medium	-6479.741*	0.000	TWEC	AFT	Low	Medium	215.481	0.839
			High	-19770.778*	0.000				High	-83.778	0.937
		Medium	High	-13291.037*	0.000			Medium	High	-299.259	0.778
	TNW	Low	Medium	-0.015	0.870		TNW	Low	Medium	-0.111	0.223
			High	0.074	0.415				High	-0.074	0.415
		Medium	High	0.089	0.329			Medium	High	0.037	0.683

(*)The mean difference is significant at the 0.05 level.

As seen in Table 5, each of the pairwise differences among the different levels of NBEC, BSEC and MPT is found to be statistically significant ($p < 0.05$) for the average flow time (AFT). However, the reverse results have been observed for TWEC. The results show that the factor levels of NBEC, BSEC and MPT have an important effect on the performance of the proposed method for the HCBS when the performance is evaluated in terms of the average flow time. Table 5 also indicates that the slight differences between different factor levels (except NBEC) are not found to be statistically significant for the total number of workers (TNW). Regarding TNW, it is concluded that the factor levels of NBEC, MPT and TWEC have not an important effect on the performance of the proposed method for the HCBS when the performance is evaluated in terms of the total number of workers.

6. Conclusion

This paper addresses the batch scheduling problem in the MHCMS by considering worker resource and flow times simultaneously-something that is largely overlooked in the literature of batch scheduling in CMS. A goal programming mathematical model is proposed, in which the first objective is minimization of the average flow time and the second is minimization of the total number of workers. Due to the complexity of the problem, we developed a heuristic method, namely the HCBS heuristic. To validate the suitability and applicability of the heuristic, it is implemented in a real life expansion joint production system in a pipeline industry. Hence, this research is thought to assist to the engineering managers with important insights to enhance control level for batch scheduling in CMS.

By the end of this research, the findings dealing with capacity requirements show that the proposed HCBS heuristic creates different level of freed-up workforce capacity for different combinations of objective function coefficients. It should also be noted that critical success factors, which are accuracy and topicality of production data, lean applications in manufacturing environment and work study, were made critical contribution to the findings of research. For this reason, attention should be paid to these critical success factors in other studies.

For the extension of the present research, other worker related issues can be considered, such as different worker skills for assignment and worker skill levels to perform operations. Moreover, in order to represent the real manufacturing systems more realistic, uncertain parameters and stochastic approaches can be added in future research. As another future research direction, the results obtained by the proposed method can be compared with some non-deterministic methods, such as particle swarm optimization (PSO), genetic algorithm (GA), and other evolutionary algorithms.

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APEM journal

Advances in Production Engineering & Management **ISSN 1854-6250**
Volume 11 | Number 3 | September 2016 | pp 207–215 Journal home: apem-journal.org
http://dx.doi.org/10.14743/apem2016.3.221 Original scientific paper

Consideration of a buyback contract model that features game-leading marketing strategies

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A B S T R A C T

Enterprises will sacrifice profits for market shares. For this reason, the make-to-stock upstream expects the downstream to order more. The paper argues the game leader sales-oriented upstream, motivating downstream make no shortage, and attempts to execute a buyback contract to reach realistic decisions. In this article, we research a supplier that is a sales-oriented leader and a retailer that is a profit-oriented follower. The retailer is required to order more than its optimal quantity. The primary analysis emphasizes either enhancing the buyback price or reducing the wholesale price. In the results, the buyback contract parameters are limited by both the sales-oriented supplier's retained earnings and the distribution of market demand. Numerical examples are given to illustrate contract parameters that affect the supply chain coordination, the order quantity of the retailer and the profit of the supply chain. The previous buyback contract literature assumes not only that the supplier and retailer are profit oriented but also that they achieve both supply-chain coordination and Pareto optimality. However, the paper discusses the parameters of the buyback contract when the supplier is sales oriented.

A R T I C L E I N F O

Keywords:
Buyback contract
Marketing strategy
Supply chain coordination

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Article history:
Received 12 June 2016
Revised 8 July 2016
Accepted 18 July 2016

1. Introduction

The making new products in many ways have done jobs. Exactly, the motor vehicle manufacturers have released new products whose functionality and service are higher than ever before due to the trend of motor vehicles purchase quota policy in China. Even the oligopolies have not hesitated to sacrifice profits to increase sales and grab market share. Hence, the marketing strategy would pull the production manufacture. Chen et al. [1] research has shown that a Website infomediary provides retailers with a demand-referral service and customers with incentive rebates. Studies have also examined rebate sensitivity and market share in the context of which policies are optimal to achieve an integrated supply chain. The importance of market share is widely recognized. Pasternack [2] study a buyback contract is one in which the supplier charges a retailer the wholesale price before the selling season and then buys back any unsold products at a buyback price at the end of selling season. Essentially, a buyback contract motivates retailers to order more. Cachon [3] points to a comparative study of classic supply-chain contracts shows that under certain circumstances, a buyback contract is equal to a revenue-sharing contact. He et al. [4], this paper investigates the revenue-sharing contract in supply chains with a sales-oriented supplier, examining both supply-chain collaboration solutions and the Pareto improvement between the supplier and the retailer when the quantity of a retailer's order falls within a certain range. In addition, it asks whether the classic buyback contract is a solution when a supplier is a game leader that is sales oriented.

The research presents the buyback contract as a return policy pursuant to which the supplier buys back any unsold products at the end of the contract period. In this scenario, the retailer orders an optimal quantity. Lee et al. [5] research the buyback price (or the price subsidy) is used to solve technical problems that lead to a decrease in a product's market price pursuant to reach on price protection in the information technology (IT) industry that discusses these problems. Yan and Huang [6], those researchers discuss the return problem in the electronics market. The solution is for the retailer to sell the unsold products online and then to deduce the optimal order quantities using both the traditional market and the electronic market. Ding and Chen [7] focus on situations in which an appropriate return policy coordinates a three-echelon supply chain, whose members will fully distribute its profit. Cai et al. [8] investigate a specific buyback contract in which the supplier subsidizes the retailer's inventory and the retailer's order quantities exceed the supplier's objective.

Traditionally, the supply-chain contracting literature has focused on aligning economically rational players' incentives. Additionally, the buyback contract research assumes that both suppliers and retailers are not only profit oriented but also achieve both supply-chain coordination and Pareto optimality. In reality, Loch and Wu [9], a portion of the research is distinct from economic incentives, providing experimental evidence that human behaviour affects economic decision making in supply-chain performance. More importantly, supply-chain parties deviate from the predictions of self-interested profit-maximization models. One study, Ho et al. [10] consider how fairness influenced economic outcomes in a supply chain and designed the supply chain contract. In another, Lin and Hou [11], empirical theoretical feedback uncovers the cause of failed buyback contract coordination by analyzing the correlation between wholesale price and buyback price. More recently, Zhang et al. [12] research has considered the loss-averse supplier and how to establish a critical ratio between buyback contracts and share revenue contracts. Another study, Sluis and Giovanni [13] provide an empirical contribution on the subject of coordination with contracts, which has turned out to be primarily based on game theory. In this paper, the supplier has greater motivation to incentivize the retailer to order more than his optimal quantity. The results show the buyback contract parameters how to adjust. A notational system is presented in section 2; the buyback contract with profit-oriented suppliers, realized supply-chain coordination (Chen et al.) [14] and Pareto optimality (Ding et al.) [15] are discussed in section 3; sales-oriented suppliers' buyback-contract strategies are discussed in section 4; numerical examples illustrate the two types of strategies in section 5; and a summary and future research are presented in section 6.

2. Notational systems

This paper assumes the supplier is the leader and the retailer is the follower in a two-echelon supply chain playing the Stackelberg game. The market demand is stochastic x, the density function $f(x)$ and cumulative distribution function $F(x)$, $F(x)$ is a monotone continuous increasing function, and has first derivative $F(0) = 0$. The list of variables below describes this article's notations. And $P(q) = \int_0^q xf(x)dx + \int_q^\infty qf(x)dx$, $I(q) = \int_0^q (q-x)f(x)dx$, $L(q) = \int_q^\infty (x-q)f(x)dx$.

q_1 (q_2) – The order quantity of the profit-oriented (sales-oriented) retailer
w_1 (w_2) – The wholesale per unit of the profit-oriented (sales-oriented) supplier
b_1 (b_2) – The buyback price per unit of the profit-oriented (sales-oriented) supplier
p – The market price per unit of product
c – The supplier's marginal cost per unit
g – The retailer's shortage cost per unit
v – The retailer's salvage value of unsold product
$P(q)$ – The sales quantity

$I(q)$ – The unsold quantity
$L(q)$ – The shortage quantity
$Pr()$ – Probability function

3. Profit-oriented supplier strategies

Because the supplier is profit oriented and strives for maximum profit, the supplier provides the set of buyback contract parameters (w_1, b_1) to the retailer. Here (w_1, b_1) are the wholesale and buyback price per unit of the profit-oriented supplier. The retailer's order quantity is according to the contract parameters above. Then, the expected profits of supplier and retailer are $E\pi_{s1}(q; w_1, b_1)$ and $E\pi_{r1}(q; w_1, b_1)$:

$$E\pi_{s1}(q; w_1, b_1) = (w_1 - \mathrm{c})q - b_1 I(q) \tag{1}$$

$$E\pi_{r1}(q; w_1, b_1) = pP(q) + (b_1 + v)I(q) - gL(q) - w_1 q \tag{2}$$

$P(q)$ are the expected sales; $I(q)$ are the expected total unsold products; and $L(q)$ are the expected shortages.

According to the formula $\frac{\partial \pi_{r1}}{\partial w_1} < 0$, the retailer's profit increases when the wholesale price decreases. When the wholesale price approaches the product cost, the expected profit of retailer, $E\pi_{r1}$, is amended by the other formula, $E\pi(q)$:

$$E\pi(\mathrm{q}) = pP(q) + vI(q) - gL(q) - cq \tag{3}$$

Eq. 3 is the optimal profit of the centralized supply chain. Plug these equations into Eq. 1 and Eq. 2, derivative with q and get the optimal order quantity of retailer q_1 and centralized supply chain q^* is satisfied with equations $F(q_1) = \frac{p+g-w_1}{p+g-(b_1+v)}$ and $F(q) = \frac{p+g-w}{p+g-c}$, respectively. The contract parameters are discussed in the context of $F(q_1)$and $F(q)$. If $b_1 = b(w_1)$, which is the buyback price, is a function of the wholesale price, then $q_1 = q^*$. Plug $b(w_1) = \frac{(w_1-\mathrm{c})(p+g-w)}{p+g-c}$ into $E\pi_{s1}(q; w_1, b_1)$ and $E\pi_{r1}(q; w_1, b_1)$, simplify them, just get: $E\pi_{r1}(\mathrm{q}; w_1, b_1) = \gamma(E\pi(q^*) + g\mu) - g\mu$; $E\pi_{s1}(\mathrm{q}; w_1, b_1) = (1-\gamma)(E\pi(q^*) + g\mu)$.

Let the parameter γ be $\gamma = \frac{p+g-w_1}{p+g-c}$. Given $w_1 > c$, then$\gamma \in (0,1)$, thus the supply chain would be coordinated by the buyback contract with the profit-oriented supplier.

4. Sales-oriented supplier strategies

Because the supplier who strives for maximum sales quantity is sales oriented, it provides the set of buyback contract parameters(w_2, b_2) to the retailer. Here (w_2, b_2) are the sales-oriented supplier's wholesale and buyback prices per unit. The retailer's order quantity is according to the contract parameters set forth above. Then, the expected profits of supplier and retailer are $E\pi_{s2}(q; w_2, b_2)$ and $E\pi_{r2}(q; w_2, b_2)$:

$$E\pi_{s2}(q; w_2, b_2) = (w_2 - \mathrm{c})q - b_2 I(q) \tag{4}$$

$$E\pi_{r1}(q; w_2, b_2) = pP(q) + (b_2 + v)I(q) - gL(q) - w_2 q \tag{5}$$

From the first-order optimal condition of Eq. 5, the optimal order quantity of retailer q_2 is satisfied with:

$$F(q_2) = \frac{p + g - w_2}{p + g - (b_2 + v)} \tag{6}$$

4.1 Maintain the wholesale price and increase the buyback price

In chapter 3, the retailer's optimal order quantity is the centralized supply chain's optimal product when the buyback parameters are $b(w_1) = \frac{(w_1-\mathrm{c})(p+g-w)}{p+g-c}$. The centralized supply chain's optimal product means that reach supply chain's Pareto optimality. However, the sales-oriented supplier expects maximum sales quantity and minimum (or even no) shortage. Then, the sales-oriented supplier proposes a new incentive contract and requires the retailer's order quantity $q_2 \in (q^*, \hat{q})$. Moreover, $\hat{q}$ makes $L(\hat{q}) = 0$. Compare $F(q_1)$ and $F(q_2)$ when the sales-oriented supplier would regulate the contract parameters to realize $q_2 \in (q^*, \hat{q})$: one is the buyback price increasing, the other is the wholesale price decreasing.

When the buyback price increases, the contract parameters (w_2, b_2) are satisfied with the following conditions: $(w_2 = w_1, b_2 > b(w_1))$ to build the model P.

$$P: \max_{b_2} F^{-1}\left(\frac{p + g - w_1}{p + g - (b_2 + v)}\right) \tag{7}$$

$$s.t. \begin{cases} E\pi_{s2}(q^*; w_2, b_2) \geq E\overline{\pi_{s2}} & (8) \\ E\pi_{r2}(\text{q}; w_2, b_2) \geq E\pi_{r1}(q^*; w_1, b_1) & (9) \\ q \in (q^*, \hat{q}) & (10) \end{cases}$$

Following is a further discussion of this model. The sales-oriented supplier has a higher amount of current revenue when the wholesale price is increased. The inventory cost would also be transferred because the retailer is expected to order products in excess of his optimal order quantity. The next problem is whether the retailer is motivated to pay more.

4.2 Decrease the wholesale price and maintain the buyback price

The supplier's strategy, which remains unchanged with regard to the wholesale price and establishes a higher buyback price, must be confronted with the retailer's capital constraint before the selling season. If the retailer has no financing, the contract will not motivate it to participate. Following is a discussion of another supplier's strategy in that case.

Model

When the wholesale price decreases, the contract parameters (w_2, b_2) are satisfied with the conditions: $(w_2 < w_1, b_2 = b(w_1))$to build the model P'.

$$P': \max_{w_2} F^{-1}\left(\frac{p + g - w_1}{p + g - (b_2 + v)}\right) \tag{11}$$

$$s.t. \begin{cases} E\pi_{s2}(q^*; w_2, b(w_1)) \geq E\overline{\pi_{s2}} & (10) \\ E\pi_{r2}(\text{q}; w_2, b(w_1)) \geq E\pi_{r1}(q^*; w_1, b(w_1)) & (11) \\ q \in (q^*, \hat{q}] & (12) \end{cases}$$

In the two models above, Eq. 7 and Eq .9 are the objectives of the supplier's decision-making in which the incentive mechanism is acted on by the contract parameters b_2 or w_2 to guarantee the retailer's maximum order quantity. Eq. 6 and Eq. 10 represent the supplier's reserved earnings. Eq. 7 and Eq. 11 represent the retailer's participation constraints. Eq. 8 and Eq. 12 are decision variables and their domain of definitions; $\hat{q}$ makes $L(\hat{q}) = 0$

For property 1, the buyback contract parameters are limited by the supplier's reserved earnings and the distribution of market demand when the supplier is sales oriented.

When the wholesale price is decreased, the retailer is motivated to order more products within the capital constraint. Indeed, the supplier's objective, which is to encourage the retailer to order more, results in an expectation of greater market share. Nevertheless, this approach does not necessarily result in higher sales.

4.3 Sales efforts

If more market demand is not created, the supplier would not believe that more orders lead to more sales. In this situation, sales effort would directly change market demand, thus affecting the retailer's order quantity. Tirole [16] shows that sales are not only influenced by market price but also (eventually) related to sales effort. This section will discuss what happens when the retailer's sales efforts satisfy the sales-oriented supplier's objective.

Model

The variable e is sales effort, D_e is stochastic market demand and increasing function. $D_e G(x,e) = Pr(D(e) \leq x)$ is distribution function and $\frac{\partial G(x,e)}{\partial e} < 0$ is a monotonic continuous increasing function. Both are changed with sales effort. $g(e)$ is the cost of the retailer's sales effort and $g(0) = 0$ is a monotonic continuous increasing function with the first derivative. $P(q,e)$ is expected sales within sales effort, $P(q,e) = E\min(x, D(e))$. $I(q,e) = E(q - D(e)^+)$

$$P'': \max_e eF^{-1}\left(\frac{p+g-w_1}{p+g-(b_1+v)}\right) \tag{13}$$

$$s.t.\begin{cases} E\pi_{s2}(q^*; w_2, b(w_1)) \geq E\overline{\pi_{s2}} & (14) \\ E\pi_{r2}(\mathrm{q}; w_2, b(w_1)) \geq E\pi_{r1}(q^*; w_1, b(w_1)) & (15) \\ q \in (q^*, \hat{q}) & (16) \end{cases}$$

Sales effort influenced order quantity and expected sales increased. However, sales effort did not solve the retailer's capital constraint.

5 Numerical examples

5.1 Set parameters

A supplier and a retailer align in a two-echelon supply chain with a buyback contract. The supplier has two potential strategies: the sales-oriented strategy and the profit-oriented strategy. Both of the strategies in the above discussion have the same parameters: the market price, $p = 10$, the product cost, $\mathrm{c} = 4$, the salvage value of unit, $g = 2$, the shortage cost of unit, $v = 1$, market demand X is subject to normal distribution, the mean is $\mu = 100$, and the standard deviation is $\sigma = 20$.

5.2 Optimal profit-oriented decisions

The expected shortage: $\mathrm{L}(QC) = 3.6089$.

A wholesale price and a buyback price form a set of buyback contract parameters. Table 1 shows that the retailer's optimal order quantities are $q_c^* = 11.18246$ and the supply-chain revenues are $\pi_c = 52.4831$ with changes in the wholesale price and buyback price. The initial wholesale price is 4 and increases one unit every time until 10; the buyback price, retailer's profit and supplier's profit correspond.

Figure 1 shows that when the supplier is profit oriented, the wholesale price is increased, leading to an increase in the supplier's profits and a decrease in the retailer's profits. However, the supply-chain revenue remains unchanged. The buyback price is higher if the wholesale price is increased.

The following discusses the three numerical strategies when the supplier is sales oriented.

Table 1 Optimal profit-oriented decisions

w	b	π_r	π_s	w	b	π_r	π_s
5	1.3750	43.4227	9.0604	8	5.5000	16.2415	36.2415
6	2.7500	34.3623	18.1208	9	6.8750	7.1812	45.3019
7	4.1250	25.3019	27.1812	q_c^*	11.1824	π_c	52.4831

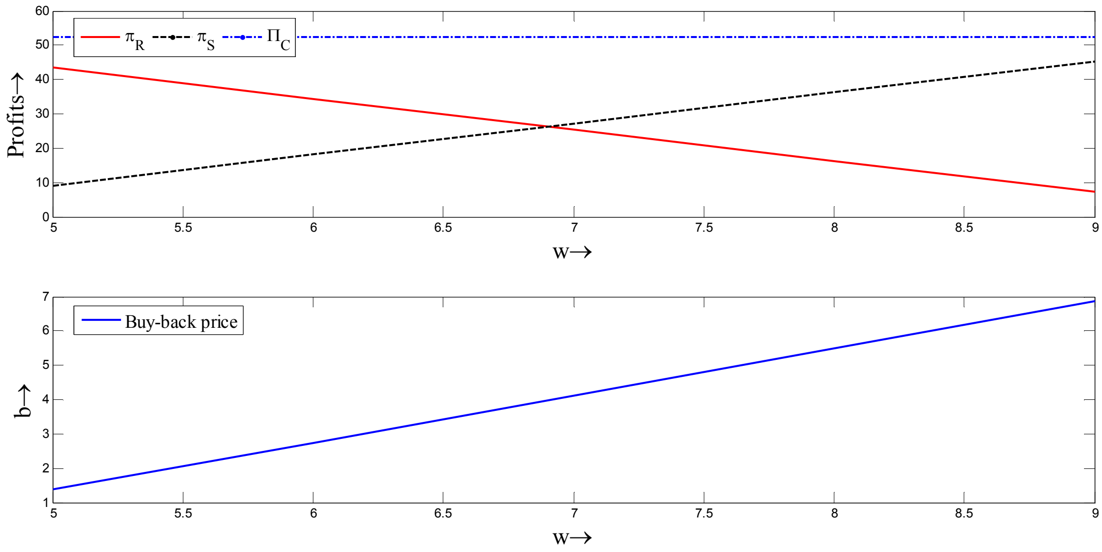

Fig. 1. The wholesale price effect on supply chain performance and buyback price

5.3 Strategy 1: Maintain the wholesale price and increase the buyback price

Here, the expected shortage in the profit-oriented scenario is still used. The five group parameters are set in Table 1: subscript 1 represents the original in the profit-oriented scenario; subscript 2 is the parameter after the buyback price was raised. b_2 is the independent variable in each group and the dependent variables are $\pi_{r2}, \pi_{s2}, \pi_2$. Table 1 is used to make a comparison. Table 2 shows all numerical information up to the incentive mechanism, when the retailer orders more to satisfy the supplier's objective. However, the supplier's lost profits are greater than those of the supply chain. In general, to reach the same order quantity q_2 than optimal quantity in the profit-oriented scenario, the supplier's losses are not equal to the supply chain's losses or the retailer's increments compared to several groups' arguments in strategy 1. The supply chain's revenue is almost unchanged front and back, as Fig. 2 indicates. The supplier's loss is less than the retailer's increments; additionally, whenever the losses or increments decrease, the wholesale price increases. In Fig. 2, the solid line and the dotted line represent the supply chain's performance in the profit-oriented and the sales-oriented scenarios, respectively. It is obvious that the retailer's profit is increasing and the supplier's profits are decreasing, which is the basis of the profit-oriented scenario. However, the increment or the decrement is gradual and the profit lines almost overlap with the increasing wholesale price.

Table 2 Sales-oriented strategy 1

w	(b_1, b_2)	(q_1, q_2)	(π_{r1}, π_{r2})	(π_{s1}, π_{s2})	(π_1, π_2)
5	1.3750→2.0234		43.4227→44.5046	9.0604→7.8694	
6	2.7500→3.3058		34.3623→35.2896	18.1208→17.0844	
7	4.1250→4.5882	111.8236→ 115.4325	25.3019→26.0747	27.1812→26.2993	52.4831→ 52.3740
8	5.5000→5.8705		16.2415→16.8597	36.2415→35.5143	
9	6.8750→7.1529		7.1812→7.6448	45.3019→ 44.7292	

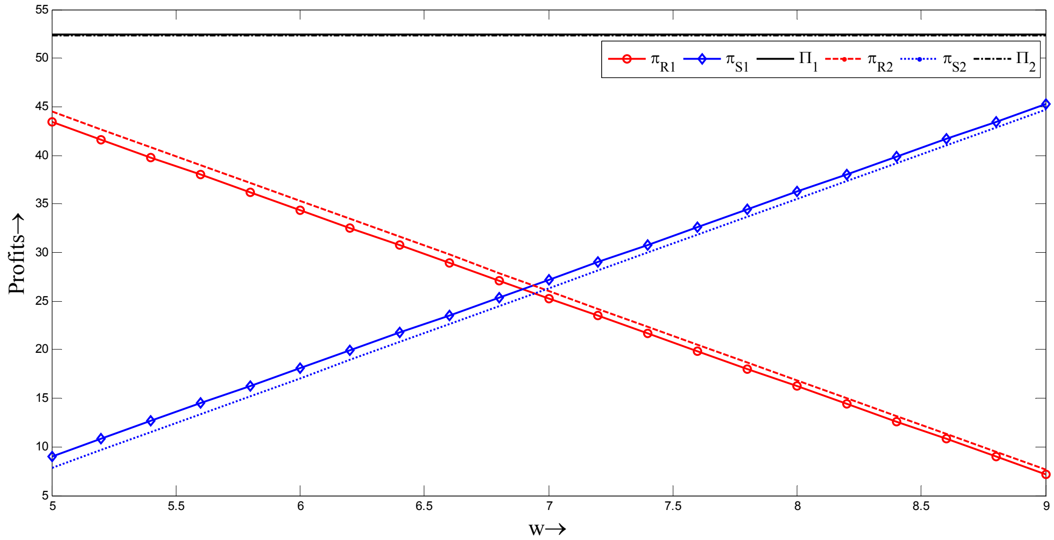

Fig. 2 Supply-chain performance after increasing the buyback price versus making the optimal decision

5.4 Strategy 2: Increase the wholesale price and maintain the buyback price

The parameters are set in accordance with Table 2. The difference is thatw_2 is the independent variable in each group. Table 3 shows the numerical incentive mechanism. Comparing strategy 1 with strategy 2 reveals some differences: each group's parameters show that it is obvious that the retailer makes more profit in strategy 2 than in strategy 1. Additionally, the supplier's decrement is more than the retailer's increments; even the supply chain's revenue remains unchanged in the sales-oriented scenario. In Fig. 3, the solid line and the dotted line are used as in Fig. 2. It is obvious that the area between the solid line and the dotted line is larger than in Fig. 2.

Table 3 Sales-oriented strategy 2

b	(w_1, w_2)	(q_1, q_2)	(π_{r1}, π_{r2})	(π_{s1}, π_{s2})	(π_1, π_2)
1.3750	5→4.4944		43.4227→49.1641	9.0604→3.2099	
2.7500	6→5.5666		34.3623→39.2835	18.1208→13.0905	
4.1250	7→6.6388	111.8236→115.4325	25.3019→29.4029	27.1812→22.9711	52.4831→52.3740
5.5000	8→7.7111		16.2415→19.5223	36.2415→32.8517	
6.8750	9→8.7833		7.1812→9.6417	45.3019→42.7323	

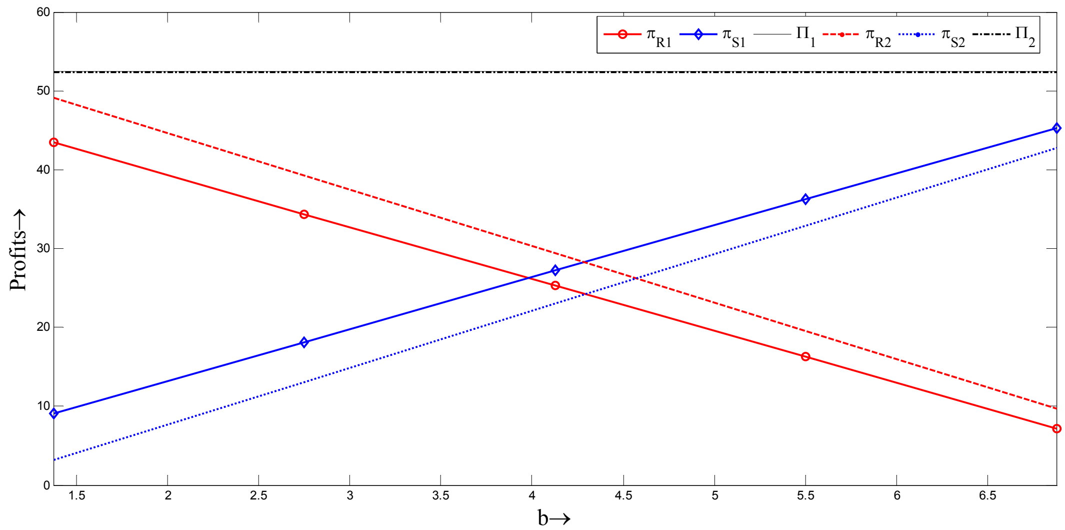

Fig. 3. Supply-chain performance after decreasing the wholesale price versus making the optimal decision

5.5 Strategy 3: Sales effort

This section discusses the retailer's sales effort to order more products. Here, assuming $g(e) = \frac{1}{2}ke^2$ (Xu *et al.*, 2004) [17], $D(e, x) = ex$. (Xu et.al 2004)[17]. k is the ratio of sales effort cost and the independent variable; the other parameters are dependent variables. The first k and e are set as a benchmark, $k = 20$, $e = 2$. k is increased by 10 every time. The retailer would decide q_e and e using the maximum profits. The calculated results are in Table 4. In accordance with Table 4, Fig. 4 describes the relationship between the independent and dependent variables:

- k and e are negatively correlated except for two inflection points, $k = 26$, $k = 52$. e experiences any change before $k = 26$ and after $k = 52$;
- k and q are negatively correlated except for two inflection points, $k = 26$, $k = 52$. q experiences any change before $k = 26$ and after $k = 52$;
- k and the retailer's profit are negatively correlated.

Table 4 Sales-oriented strategy 3

k	e	q_e	π_e
20	2.0000	22.4248	65.2061
30	1.7600	19.7194	46.0887
40	1.3200	14.7896	34.5064
50	1.0600	11.8437	27.5562
60	1.0000	11.1824	22.4831

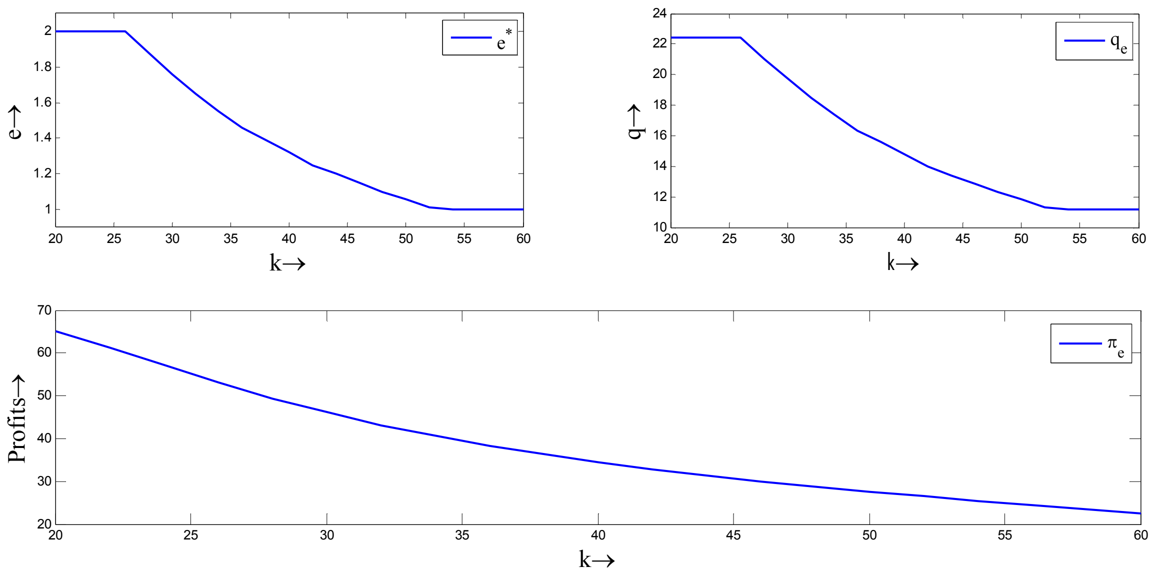

Fig. 4 Relationship of the sales effort cost ratio

6. Conclusion

This paper investigates three supplier strategies to motivate the retailer to order more than its optimal quantity through the mechanism of the buyback contract. The supplier's marketing strategy types in the two-echelon supply chain include both profit-oriented and sales-oriented strategies. Following is the main conclusion:

- The new buyback contract parameters are limited by both the reserved earnings of the supplier and the distribution of market demand when the supplier is sales oriented; the supplier's expected profit is a decreasing function of the wholesale price or the buyback price. In contrast, the retailer's expected profit is an increasing function of the wholesale price or the buyback price. The supplier would prefer a higher buyback price to stimulate the retailer to order more, but the retailer would prefer a lower wholesale price. The reason for these preferences is that from which the supplier or the retailer benefits on the transfer-payment front.

- Based on the former two figures, the supply-chain revenue experiences almost no change when the supplier motivates the retailer to order more than its optimal quantity. In that situation, it is possible to satisfy the sales-oriented supplier's objective. The issue is how to distribute the supply chain's profit. However, all strategies above are based on the same expected shortage in quantity, meaning that more orders create the need for more sales. The former two strategies do not solve this problem.
- The order quantity must be increased if the retailer strengthens his sales effort. Strategy 3 discusses the retailer's sales efforts, which are made at a certain cost to the retailer. This situation requires an optimal level of sales effort to obtain more profits; however, it leads to smaller orders.

Further research on the fair distribution of supply-chain revenue, with the retailer ordering more and selling as much as possible to effect the supplier's strategy, should be conducted in the future.

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APEM journal
Advances in Production Engineering & Management
Volume 11 | Number 3 | September 2016 | pp 216–226
http://dx.doi.org/10.14743/apem2016.3.222
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

A green production strategies for carbon-sensitive products with a carbon cap policy

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ABSTRACT

This paper discusses the production strategies used by manufacturers of carbon-sensitive products that have a carbon cap Policy under both deterministic demand and stochastic demand. In this study, we examine green manufacturing strategies for carbon-sensitive products under carbon cap policy regulations. We primarily consider the two scenarios of deterministic demand and stochastic demand. When the carbon cap Policy regulation has no restriction to the production of the manufacturers, the higher the carbon sensitivity coefficient of the product, the lower the profit of the manufacturing enterprise. When carbon cap Policy regulation of manufacturing enterprise production is a constraint, for the deterministic demand, with the higher carbon sensitive coefficient, manufacturing enterprise profit is higher; for stochastic demand, With the increasingly high carbon sensitive coefficient, manufacturing enterprise profit is low. Through the above research, the conclusion of this paper has reference value and guiding role to carbon-sensitive products' green production strategies with a carbon cap policy.

ARTICLE INFO

Keywords:
Production strategy
Carbon sensitive
Carbon cap policy

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Article history:
Received 12 June 2016
Revised 5 July 2016
Accepted 18 July 2016

1. Introduction

Productivity has greatly improved since the Industrial Revolution. However, that production consumes a significant amount of energy and produces large quantities of carbon dioxide, which has triggered changes in the global climate. The International Energy Agency (IEA) estimates a world gross domestic product (GDP) of 70 trillion in 2011 and 3.4 percent average annual growth from 2008 to 2035. With economic development, energy consumption has greatly increased, and our country will soon be confronted by the serious issue of energy-resource shortages. If each 1 percent GDP increase results in a 0.47 percent energy-consumption increase, world economic development will primarily rely on fossil fuels. More importantly, a non-profit government consulting institute, the LMI Research Institute, has stated that commercial activity in all manufacturing sectors count for much in carbon emissions. The carbon emissions produced by the manufacturing industry are caused by the use of raw materials (the transportation of semiconductors, steel, energy resources), manufacturing processes (heating treatments, welding, pressing) and waste-disposal process (carbon emission from waste-disposal plants).

To mitigate global warming and reduce environmental pollution, governments worldwide are actively responding by publishing policies intended to solve this problem. The primary issue is how to transform human production and lifestyles to achieve a low-carbon economy and lifestyle. The Kyoto protocol provided a standard and direction for solving the global-warming problem. The implementation of a carbon quota has been derived from the Kyoto Protocol, which aims to achieve effective emissions reduction through a binding, legal requirement that greenhouse-gas emissions be maintained within a certain range. Furthermore, with an increase in environmental protection consciousness, consumers hope decrease carbon emissions as well as lower the prices, and enhance environmental protections. However, industrially manufactured products are carbon-sensitive products. With the establishment of a carbon quota mechanism, enterprises must consider the issue of carbon emissions. Simultaneously, because consumers are more likely to buy products with low carbon and environmental protections, a product's carbon sensitivity also has an impact on product demand.

In this context, production enterprises can both improve market demand and increase corporate profits by emphasizing the low-carbon , environmentally protective characteristics of carbon-sensitive products. Therefore, when an enterprise is required to adopt a carbon quota policy, the question of how it can realize sustainable development and social responsibility while growing its profits becomes a key aspect of both enterprise operation and enterprise development. Simultaneously, this issue has become the subject of major research both at home and abroad. Therefore, research on the production strategy of carbon-sensitive products under a carbon cap policy can provide the basis of and reference for an enterprise's production activities.

There have been relevant studies both at home and abroad on the production strategy associated with carbon quota policies. Hong et al. [1] considers retailer ordering and pricing decisions under carbon cap policies and discusses the impact of carbon emissions trading on retailer ordering, pricing and maximizing expected profit. Bouchery et al. [2] add carbon cap-and-trade to the inventory model, analyzing the effect of carbon quotas on the inventory model. Chaabane et al. [3] find that regarding carbon emissions trading, with the establishment of a relevant supply chain model, carbon limits can effectively reduce carbon emissions. Benjaafar et al. [4] study the impact of carbon limitation and transaction policies on enterprises' behavior associated with investment, production, inventory and ordering decisions. Enterprises can maximize profits by modifying order quantity. Zhang and Xu [5] investigate the multi-item production-planning issue associated with carbon cap-and-trade mechanisms where an enterprise produces vary products that fulfil independent stochastic demands with a common capacity and carbon emission quota; those authors use numerical analyses both to illustrate their findings and to identify managerial insights and policy implications. Using an economic order quantity (EOQ) model, Chen et al. [6] provide a situation where it is possible to lower emissions by altering the number of orders. They also provide the situations where the emissions reduction is comparatively greater than the cost increase. Moreover, they study the elements that influences differences in the magnitude of decrease in emission and rise in cost Ma et al. [7] demonstrates the effectiveness of the use of cap-and-trade policy as a mechanism to encourage manufacturers to reduce carbon emissions while obtaining expected profits through their use of green technology inputs. Qi et al. [8] stress the value of centralized management of value chain decisions and sharing of knowledge for Mass customization capability.

Regarding to economic benefit and emission reduction, a multi-goal optimization model has been set by Qu et al. to show their relationship; they show that when it compared with the original policy, the collection of diverse emission-reduction policies make greater-efficiency emission reduction and less economic loss. Mutingi [10] plays an important role in both academics and professionals in the field of green supply-chain management. First, Mutingi's study provides a great deal of information to construct a practical tool or framework for managers in the development of green supply-chain tactics given the certain industrial situations where those tactics are used. Second, Mutingi's taxonomic framework provides managerial view about the effects of the selection of certain strategies for a supply chain's operations policies.

Using a duopoly model, Wang and Wang [11] quantitatively explore the impact of a carbon offsetting scheme on both emission-trading participants' profits and industry output by drawing on the advanced experience of carbon-offsetting schemes in developed countries. A negative relationship between firms' carbon intensity and their equilibrium output in the product market is revealed from the outcomes. Furthermore, that study presents a commencement for the compared importance of duopoly enterprises' carbon intensity where their absolute output will differ dramatically.

Sengupta [12] considers that when consumers are aware of a product's green and environmental protections, they assume that green technology can both improve the production of green products and offer environmental protection; an appropriate increase in prices will generate additional profits. Koren et al. [13] analyses the effect of technical and organizational views on the product complexity and to identify where most incentives for innovation initiate, and the influence on the product complexity. Buchmeister et al. [14] think the implication of weak demand discrepancy and level constraints within the supply chain on the bullwhip effect was evident.

Liu et al. [15] use a Stackelberg model to study the problem of competition in the two stages of the supply chain, discussing not only product competition among suppliers but also competition among retailers. Those authors consider how suppliers and retailers can both obtain more benefits and improve their level of competitiveness. Xu and Zhao [16] show that supply chain cooperation can raise the emissions reduction level and increase the expected total profit. Finally, the effects of different parameters on the coordination of supply chain's performance are discussed. Li et al. [17] through the establishment of the Stackelberg game model, it is concluded that the optimal emission reduction level and the optimal proportion of the retail and supply, and the optimal profit value of the two in different contract forms. Huang and Zhao [18] study bargaining between manufacturers and retailers in the case of consumers' low carbon preferences, analysing both the influence of a manufacturer's pricing on the retailer and the function of the two parties.

Because of the relevant environmental protection policy and consumer awareness of both environmental protection and low carbon emissions, research on carbon-sensitive product manufacturers' production strategies under a Cap policy can provide manufacturers with valuable information.

2. Problem statements and basic assumptions

This paper studies a manufacturer in a monopoly market. The manufacturer produces only one product (for example, a smart phone); the remaining inventory is produced in accordance with residual value processing at the end of a sales period. The product's decision-making value is its production; the manufacturer's decision-making goal is profit maximization. The government has specified the largest carbon emissions E, under its carbon cap policy. To achieve carbon-emissions reduction targets, the carbon emissions of manufacturers' production activities cannot exceed the maximum level set by the government. At the same time, consumers demand low-carbon and environmental-protection features in their products; those features are associated with the products' carbon-sensitive coefficient k. Therefore, consumer demand influences production. This paper primarily studies the following two issues:

Under the deterministic demand condition, demand is equal to the economic order quantity (EOQ) and thus, to both a manufacturer's production strategy with a carbon cap policy and the influence of a carbon-sensitive coefficient on profits; and

Under the stochastic demand condition, requirements are related to price and a product's degree of carbon sensitivity and thus, to both a manufacturers' production strategy with a carbon cap policy and the influence of a carbon-sensitive coefficient on profits.

For convenience, the model's main variables are listed below:

k – Carbon-sensitive coefficient
e – Product's per-unit carbon emissions
E – Government limit on carbon emissions
a – Unit of time of potential market demand
D – Deterministic demand per unit of time
Q – Production
v – Residual value per unit product
A – Deterministic costs of each order at a particular time
h – Annual inventory holding cost per unit product
c – Cost of production per unit product
p – Unit price of the product
g – Shortage cost of one unit of the product

3. Deterministic demand model establishment and analysis

Under the deterministic demand condition, demand is equal to EOQ and the relationship between demand and the carbon-sensitive coefficient k is $D = a - ke(D, a, k, e > 0)$.

3.1. Basic model

In the case of no carbon constraints, take the related parameters into the EOQ formulae:

$$TC = cD + \frac{D}{Q}A + \frac{Q}{2}h \tag{1}$$

TC of Q derivative:

$$\frac{dTC}{dQ} = \frac{(a - ke)A}{Q^2} + \frac{h}{2}$$

Make $\frac{dTC}{dQ} = 0$, and obtain the optimal production:

$$Q^* = \sqrt{\frac{2(a - ke)A}{h}} \tag{2}$$

The optimal profit of the manufacturer is: $\pi^*(Q) = (p - c)Q^*$, that is,

$$\pi^*(Q) = (p - c)\sqrt{\frac{2(a - ke)A}{h}} \tag{3}$$

by Eq. 3

Proposition 1: In the absence of a carbon quota restriction, if other conditions remain unchanged, the optimal profit $\pi^*(Q)$ is a decreasing function of the carbon-sensitive coefficient k.
Proof:
$\pi^*(Q)$ of k derivative:

$$\frac{d\,\pi^*(Q)}{dk} = -\sqrt{\frac{2e^2A}{h(a - ke)}} < 0$$

The profit is a decreasing function $\pi^*(Q)$ of the carbon-sensitive coefficient k; with an increase in k, $\pi^*(Q)$ decreases, while with a decrease in k, $\pi^*(Q)$ increases.
End of proof.

3.2. Manufacturers' production strategy under a carbon cap policy

Under the carbon-limitation condition, the EOQ can be obtained:

$$TC = cD + \frac{D}{Q}A + \frac{Q}{2}h \tag{4}$$

$$s.t. eQ \leq E \tag{5}$$

The constraint condition means that the total carbon emissions in the enterprise's production activities shall not exceed the amount of carbon that is emitted by the government. By discussing the optimal production strategy in this case, the following theorems are obtained.

Theorem 1: Under the deterministic demand condition, manufacturers of carbon-sensitive products are subject to the carbon quota policy under the regulation of the optimal production $Q^a \leq Q^*$.
Proof:
Let $\varphi \geq 0$, the constraint conditions can be:

$$eQ - E \leq 0 \tag{6}$$

$$\varphi(eQ - E) = 0 \tag{7}$$

$$\frac{(a-ke)A}{Q^2} + \frac{h}{2} - \varphi e = 0 \tag{8}$$

When $\varphi = 0$, by Eq. 8 $\frac{dTC}{dQ} = 0$; therefore $Q^a \leq Q^*$, $eQ^* \leq E$.
When $\varphi > 0$, by Eq. 8, $\frac{dTC}{dQ} = \frac{(a-ke)A}{Q^2} + \frac{h}{2} = \varphi e > 0$; therefore $Q^a < Q^*$.
End of proof.

In summary, the optimal production of enterprises under carbon limitation $Q^a \leq Q^*$.

Theorem 1 shows that when demand is determined, the optimal production of manufacturing enterprises in the case of carbon limits is not greater than their production in the case of no carbon limits. Carbon-quota policies affect the production activities of manufacturing enterprises.

Corollary 1: Deterministic demand, the expected profit of carbon-sensitive product manufacturing enterprises with a Carbon cap Policy $\pi(Q^a) \leq \pi(Q^*)$.
Proof:
By Theorem 1
When $eQ^* \leq E$, then $Q^a = Q^*$, so we obtain $\pi(Q^a) = \pi(Q^*)$,
When $eQ^* > E$, then $Q^a < Q^*$, so we obtain $\pi(Q^a) < \pi(Q^*)$.
End of proof.

In summary, the expected profits of enterprises under carbon limitation $\pi(Q^a) \leq \pi(Q^*)$.

Corollary 1 shows that the expected profit of the manufacturing enterprises in the case of carbon limits is not greater than those enterprises' expected profits in the case of no carbon limits.

For manufacturing enterprises, there are two types of production activities:

1. When the carbon cap is far greater than an enterprise's total carbon emissions, the enterprise need not be concerned about production problems.
2. When a manufacturing enterprise's carbon emissions associated with increased production exceeds the carbon limits, the enterprise must adjust its production to remain within the limits, and the enterprise will be concerned about the cost of a shortage caused by its production adjustment. In that case, the enterprise's production is $Q = \frac{E}{e}$. For the enterprise to establish the expected profit model in the two cases, its expected profit in the event of a carbon quota policy is expected to be as follows:

$$\pi^a(Q^a) = \begin{cases} (p-c)Q^* & eQ^* \leq E \\ (p+g-c)\frac{E}{e} - Q^*g & eQ^* > E \end{cases} \tag{9}$$

Theorem 2:
1. When the $eQ^* \leq E$, the profit function of a manufacturer of carbon-sensitive products π^a is a decreasing function of the carbon-sensitive coefficient k, and with a decrease in k, π^a increases, while with an increase in k, π^a decreases.
2. When the $eQ^* > E$, the profit function of a manufacturer of carbon-sensitive products π^a is an increasing function of the carbon-sensitive coefficient k, and with a decrease in k, π^a decreases, while with an increase in k, π^a increases.

Proof:
1. Because $eQ^* \leq E$, equivalent to a non-carbon cap, with a proof of theorem 1.
2. When $eQ^* > E$, $\pi^a(Q^a)$ of k derivative:

$$\frac{d\pi^a(Q^a)}{dk} = g\sqrt{\frac{2Ae^2}{h(a-ke)}} \tag{10}$$

Because $g\sqrt{\frac{2Ae^2}{h(a-ke)}} > 0$, the profit function π^a is an increasing function of the carbon-sensitive coefficient k; with a decrease in k, π^a decreases, while with an increase in k, π^a increases.

<u>*End of proof.*</u>

In summary, the demand is determined, there is a carbon quota policy regulation, and the optimal production quantity of manufacturing enterprises for $Q^* = \sqrt{\frac{2(a-ke)A}{h}}$ if carbon emissions from manufacturing enterprises are far less than the carbon limits and will not exceed the carbon limits. With an increased carbon-sensitive coefficient k, manufacturing enterprises might consider it appropriate to reduce production and increase profits. With a decrease in the carbon-sensitive coefficient k, manufacturing enterprises might consider it appropriate to reduce production and increase profits. With a decrease in the carbon-sensitive coefficient, manufacturing enterprises can appropriately increase production and profits. If production increases, a manufacturing enterprise's carbon emissions will exceed the carbon quota and the enterprise needs to control production activities. With an increase in the carbon-sensitive coefficient k, manufacturing enterprises can appropriately increase production and then improve profits. With a decrease in the carbon-sensitive coefficient k, manufacturing enterprises can consider appropriately reducing production and increasing profits.

3.3. Numerical analysis

From the model solution, in a carbon-sensitive demand situation, the carbon-sensitive coefficient will affect the manufacturer's optimal production and maximum profit. To understand the influence of the carbon-sensitive coefficient and the carbon cap policy on the manufacturers' optimal production and the maximum profit, the following numerical analysis method was used to analyze the sensitivity of the parameters.

For the convenience of numerical analysis, let $a = 100$, $e = 10$, $A = 10$, $h = 20$, $p = 100$, $c = 50$, $g = 30$, $E = 80$, $e = 10$.

Making $k \in (1, 10)$, we can obtain Fig. 1 and Fig. 2. From Fig. 1 and Fig. 2, we can see that with the decrease in both the carbon-sensitive coefficient and production, manufacturer's profits first decrease and then increase, which means that when a carbon cap policy does not work, with the increase in the carbon-sensitive coefficient, profits decrease. When the carbon cap policy works, with the increase in the carbon-sensitive coefficient, profits increase. The optimal production at this time is $Q^* = \sqrt{\frac{2(a-ke)A}{h}}$ = 9.75.

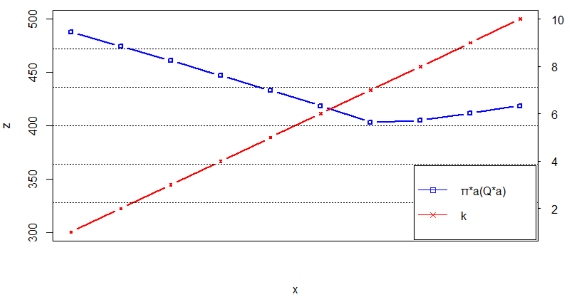

Fig. 1 Carbon-sensitive coefficient impact on profits

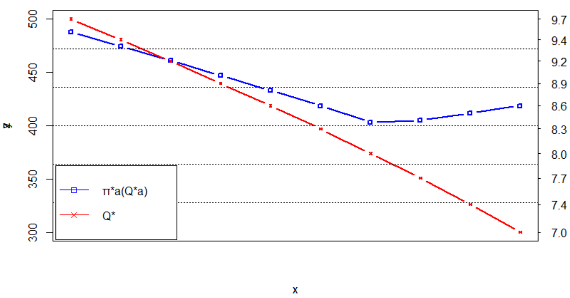

Fig. 2 Production impact on profits

4. The stochastic demand model establishment and analysis

With the stochastic demand, make x as a stochastic demand and obey follow the probability density function of the demand for $f(\cdot)$ distribution. According to the demand function and supply function, the price function for the relationship with the carbon-sensitive coefficient k is: $p = j - keQ$, ($j, k, e, Q > 0$, k as the carbon-sensitive coefficient)

4.1. Basic model

In the case of no carbon constraints, we construct the model according to the relationship of price and the carbon-sensitive coefficient function, combined with the newsboy structure of profit model for production Q:

$$\pi(Q) = (j - keQ - v)\int_0^Q xf(x)dx - (c - v)\int_0^Q Qf(x)dx + (j - keQ + g - c)\int_Q^\infty Qf(x)dx - g\int_Q^\infty xf(x)dx \tag{11}$$

If we make

$$\frac{d\pi(Q)}{dQ} = (j + g - c) - 2keQ + ke\int_0^Q F(x)dx = 0$$

we then obtain

$$j + g - c = \left(2Q - \int_0^Q F(x)dx\right)ke$$

For ease of calculation, make $G(Q) = 2Q - \int_0^Q F(x)dx$. The optimal production is as follows:

$$Q^* = G^{-1}\left(\frac{j + g - c}{ke}\right) \tag{12}$$

$\pi(Q)$ of k derivative allows us to obtain

$$\frac{d\pi(Q)}{dk} = -eQ[\int_0^Q xf(x)dx + \int_Q^\infty Qf(x)dx] < 0 \tag{13}$$

Proposition 2: When demand is stochastic, there is no carbon quota policy constraint and the profit of a manufacturer of carbon-sensitive products $\pi(Q)$ is a decreasing function of the carbon-sensitive coefficient k; with an increase in k, $\pi(Q)$ decreases, while with a decrease in k, $\pi(Q)$ increases.

Proof:

From (12), optimal production Q^* is a decreasing function of the carbon-sensitive coefficient k, The general model of the profit function is: $\pi = (p - c - v)\ Q^*$. Profit π is proportional to the carbon-sensitive coefficient Q^*, and profit π has an inverse relationship with the carbon-sensitive coefficientk; with an increase in k, π decreases, while with a decrease in k, π increases. In conclusion, the results are the same as for (13), and the proof is complete.

End of proof.

4.2. Manufacturers' production strategy under carbon cap policy

Under the carbon cap policy, carbon emissions in manufacturers' production activities must not exceed the government's largest carbon emissions. The largest production for manufacturers is $\frac{E}{e}$.

Through a discussion of the optimal production strategy in this case, the following theorems are obtained:

Theorem 3: Under conditions of stochastic demand, a manufacturer of carbon-sensitive products has a carbon cap policy of its optimal production $Q^a \leq Q^*$.
Proof:
Make $\varphi \geq 0$, can be obtained by constraint conditions:

$$eQ - E \leq 0 \tag{14}$$

$$\varphi(eQ - E) = 0 \tag{15}$$

$$(j + g - c) - 2(ke)Q + ke\int_0^Q F(x)dx - \varphi e = 0 \tag{16}$$

When $\varphi = 0$, using Eq. 16 we can obtain $\frac{d\pi(Q)}{dQ} = 0$, therefore, we can obtain $Q^a \leq Q^*$, $eQ^* \leq E$.
When $\varphi > 0$, using Eq. 16 we can obtain $\frac{d\pi(Q)}{dQ} = (j + g - c) - 2(ke)Q + ke\int_0^Q F(x)dx = \varphi e > 0$, therefore, we can obtain $Q^a < Q^*$.
End of proof.

In summary, the optimal production of enterprises under carbon limitation is $Q^a \leq Q^*$.
Theorem 3 shows that when the demand is stochastic, the optimal production of manufacturing enterprises in the case of carbon limits is not greater than the optimal production in the case of no carbon limits. The carbon quota policy has an effect on the production activities of manufacturing enterprises.

Corollary 2: Under conditions of stochastic demand, the expected profit of manufacturers of carbon-sensitive products with a carbon cap policy $\pi(Q^a) \leq \pi(Q^*)$.
Proof:
From theorem 3:
When $eQ^* \leq E$, then $Q^a = Q^*$, and we can obtain $\pi(Q^a) = \pi(Q^*)$.
When $eQ^* > E$, then $Q^a < Q^*$, and we can obtain $\pi(Q^a) < \pi(Q^*)$.
End of proof.

In summary, enterprises' expected profit under a carbon limitation is $\pi(Q^a) \leq \pi(Q^*)$.
Corollary 2 shows that manufacturers' expected profit in the case of carbon limits is not greater than in the case of no carbon limits. The carbon quota policy has an effect on manufacturers' profits.
For manufacturing enterprises, there are two types of production activities.

1. When the carbon cap is far greater than the manufacturer's total carbon emissions, the manufacturer need not be concerned about production problems.
2. When the manufacturer's carbon emissions under increased production exceeds carbon limits, it must adjust its production to comply with the carbon limits while considering the shortage cost caused by that production adjustment. At this time, the production of manufacturing enterprises is $Q = \frac{E}{e}$. For manufacturing enterprises to establish the expected profit model in two cases, we obtain the expected profit model for the manufacturing enterprises under a carbon quota policy.

When the carbon cap is far greater than a manufacturer's total carbon emissions, the manufacturer need not be concerned about a production problem; its profit model is the same as its profit model under the condition of no carbon limits, which is (11). From Proposition 2, manufacturers of carbon-sensitive products profit $\pi(Q)$ is a decreasing function of carbon-sensitive coefficient k, with the increase of k, $\pi(Q)$ decreased; with the decrease of k, $\pi(Q)$ increased.
When a manufacturer's carbon emissions increase with increased production, the production of a certain amount exceeds the carbon quota and the optimal profit model of the production of Q can be obtained by (11):

$$\pi^a(Q^a) = [j - (ke)Q - v]\int_0^{\frac{E}{e}} xf(x)dx - (c - v)\int_0^{\frac{E}{e}} \frac{E}{e} f(x)dx + [j - (ke)Q + g - c]\int_{\frac{E}{e}}^{\infty} \frac{E}{e} f(x)dx - g\int_{\frac{E}{e}}^{\infty} xf(x)dx \tag{17}$$

$$\mathrm{s.t.\,eQ} \leq \mathrm{E} \tag{18}$$

Bring $Q = \frac{E}{e}$ into (13), and obtain

$$\frac{d\pi^a(Q^a)}{dk} = -E[\int_0^Q xf(x)dx + \int_Q^{\infty} \frac{E}{e} f(x)dx] < 0 \tag{19}$$

The profit function π^a is a decreasing function of the carbon-sensitive coefficient k, with an increase in k, π^a decreases; with a decrease in k, π^a increases.

In summary, when the demand is stochastic, the optimal production $Q^* = G^{-1}\left(\frac{j+g-c}{ke}\right)$ at this time. If a manufacturer's carbon emissions are far less than the carbon limits and will not exceed those limits, with an increase in the carbon-sensitive coefficient k, manufacturing enterprises could consider it appropriate to reduce production and increase profits. With a decrease in the carbon-sensitive coefficient k, manufacturing enterprises can consider an appropriate increase in production and increase profits. If production increases, manufacturers' carbon emissions will exceed the carbon quota, and the enterprise needs to control its production activities. With an increase in the carbon-sensitive coefficient k, manufacturing enterprises might consider an appropriate reduction in production, thus improving their profits. With a decrease in the carbon-sensitive coefficient k, manufacturing enterprises can consider an appropriate production increase, thus increasing their profits.

4.3. Numerical analysis

Based on the model solution, in considering the carbon-sensitive demand situation, the carbon-sensitive coefficient will affect a manufacturer's optimal production and maximum profit. To more intuitively understand the influence of the carbon-sensitive coefficient and the carbon cap policy for manufacturers' optimal production and the maximum profit, below we demonstrate a numerical-analysis method of analysing the sensitivity of the parameters.

To conform to the general situation, assuming that market demand x satisfies normal distribution, make $x = max\ (\tilde{x}, 0)$, x satisfies a standard normal whose distribution average is 100 and variance is 10, that $\tilde{x} \sim N(100, 10^2)$. Because $p(\tilde{x} < 0)$ is small enough, it can be neglected. For ease of calculation, make $\tilde{x} = x$, and make $c = 30, v = 9, g = 10, e = 2, E = 150, j = 134.8$. We use MATLAB software (Math Works Corporation, Natick, U.S.A, Algorithm development; data visualization) to analyse the sensitivity of k and Q, resulting in Fig. 3 and Fig. 4.

As seen from Fig. 3, under the carbon cap policy regulation, there is a higher carbon-sensitive coefficient and lower profit. As seen Fig. 4, with increased production, the manufacturer's profits first increase and then decrease, which means that when the carbon cap policy does not work, with the increase of the carbon-sensitive coefficient, profits increase. When the carbon cap policy works, with the increase of the carbon-sensitive coefficient, profits decrease. Therefore, the optimal production is $Q^* = G^{-1}\left(\frac{j+g-c}{ke}\right) \approx 110$.

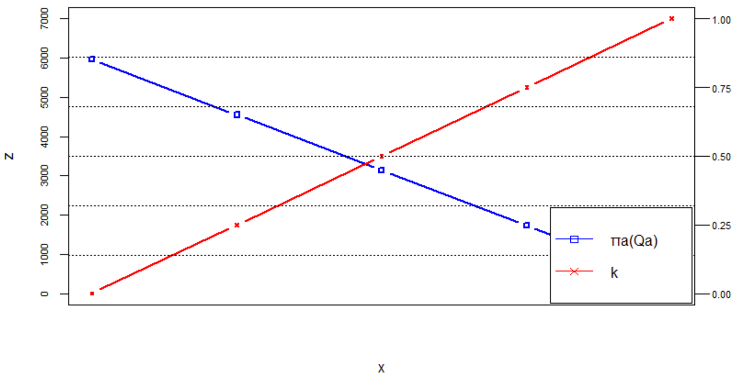

Fig. 3 Carbon-sensitive coefficient impact on profits

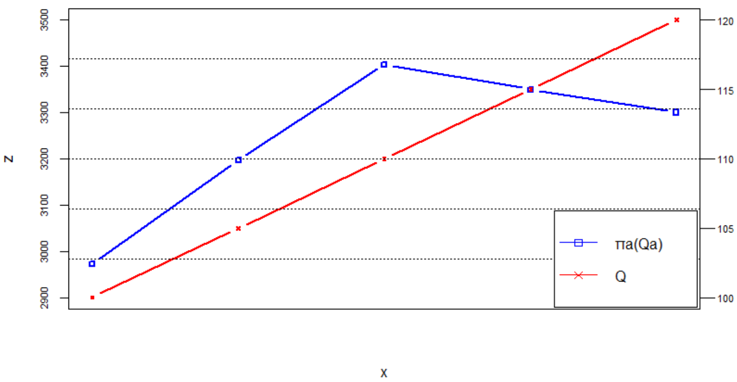

Fig. 4 Production impact on profits

5. Conclusion

This paper studied the production strategy of manufacturers of carbon-sensitive products that have a carbon cap policy. Using a reasonable assumption and example (for example, a smart phone manufacturer), it discussed the production strategy under both deterministic demand and stochastic demand, along with the influence of a carbon-sensitive coefficient on profits. The following conclusion can be drawn: If there is a carbon cap policy regulating manufacturers' production, whether under deterministic demand or stochastic demand, manufacturers will have higher carbon-sensitive coefficient products and lower profits. In this case, manufacturers engage in optimal production. When a carbon cap policy regulation plays a restrictive role in manufacturers' production, under deterministic demand, there will be a higher product carbon-sensitive coefficient and higher profits, and in this case, manufacturers engage in optimal production. Under stochastic demand, there are higher carbon-sensitive coefficient products and lower profits, in this case, manufacturers engage in optimal production. The results presented by the manufacturers studied in this paper can be applied to most industries with various probability density functions of demands, and optimality is easily obtained because the solution is expressed analytically.

This paper suffers from certain disadvantages. First, it only considers the existence of a carbon cap policy. Without simultaneously considering a Cap-and-trade, this article does not consider cost increases resulting from the use of green technology to reduce carbon emissions. These issues should be studied in the future. This paper, which is based on a reasonable hypothesis and an established model, can provide recommendations for sensitive product manufacturers' production strategies that are subject to carbon cap policy.

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APEM journal
Advances in Production Engineering & Management
Volume 13 | Number 3 | September 2016 | pp 227–238
http://dx.doi.org/10.14743/apem2016.3.223
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Investigation of dynamic elastic deformation of parts processed by fused deposition modeling additive manufacturing

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A B S T R A C T

Fused deposition modeling (FDM) has been recognized as an effective technology to manufacture 3D dimensional parts directly from a digital computer aided design (CAD) model in a layer-by-layer style. Although it has become a significantly important manufacturing process, but it is still not well accepted additive manufacturing technology for load-carrying parts under dynamic and cyclic conditions due to many processing parameters affecting the part properties. The purpose of this study is to characterize the FDM manufactured parts by detecting how the individual and interactive FDM process parameters will influence the performance of manufactured products under dynamic and cyclic conditions. Experiments were conducted through fractional factorial design and artificial neural network (ANN). Effect of each parameter on the dynamic modulus of elasticity was investigated using analysis of variance (ANOVA) technique. Furthermore, optimal processing parameters were determined and validated by conducting verification experiment. The results showed that both ANN and fractional factorial models provided good quality predictions, yet the ANN showed the superiority of a properly trained ANN in capturing the nonlinear relationship of the system over fractional factorial for both data fitting and estimation capabilities.

A R T I C L E I N F O

Keywords:
Additive manufacturing
Fused deposition modeling (FDM)
Dynamic modulus of elasticity
Fraction factorial design
Artificial neural network (ANN)
Process parameters
Analysis of variance (ANOVA)

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Article history:
Received 18 June 2016
First Revision 22 August 2016
Second Revision 28 August 2016
Accepted 29 August 2016

1. Introduction

Fused deposition modeling (FDM) process is the most popular Stratasys-patented additive manufacturing technology. FDM is gaining importance in many manufacturing applications due to its ability to create complex prototypes without requiring any tools [1]. This process builds 3D shapes from a digital CAD file in a layer-by-layer format from the bottom by melting and extruding a fine filament of thermoplastic from the extrusion nozzle onto a base. The nozzle moves horizontally and vertically over the build table to translate the dimensions of part into the X, Y and Z axes.

Over the past decade, FDM process has gained increasing attention in the field of 3D manufacturing products. Although FDM has become a more sophisticated and the range of available materials continuing to grow, the application of this process in various industries is still not yet a fully accepted as a mature technique due to lower mechanical performance and performance of the fabricated parts compared with traditional manufacturing processes such as sheet metal forming, thermoforming and injection molding. The main reason for poor mechanical performance of FDM built parts is the existence of a great number of intervening processing conditions affecting the overall part quality[1]. For instance, incorrect settings of operating parameters can cause defects on the manufactured products, such as void structures. Hence, it is essential to understand and optimize the impact of operating conditions during on the processed prototypes.

During last couple of decade's extensive research has been carried out with limited success on optimizing FDM operating parameters for various quality characteristics such as mechanical properties, surface roughness, build quality and dimensional accuracy. For example, Wang et al. [2] reported that the mechanical performance can highly affected by part direction. This study also revealed that the highest mechanical strength can be obtained when the part was manufactured with minimum z-height. Rayegani and Onwubolu [3] have carried out an experiment on the impact of FDM operating conditions on mechanical strength of build parts. The results from this study have shown that small road width, negative air gap and zero build direction can improve the mechanical strength significantly. Sood et al. [4] concluded that thick layers and rasters with zero raster to raster air gap improve the mechanical characteristics significantly. Christiyan et al [5]reported that using low printing speed and low layer thickness can effectively improve the mechanical performance of FDM built prototypes. Impens and Urbanic [6] investigated the influence of post-processing settings on the mechanical characteristics for built parts. They found that build direction is the key factor in optimizing tensile and compression strengths for processed parts. Recently, Lanzotti et al. [7] studied the impact of process parameters like infill direction, slice height and perimeters on the prototype strength. This study reported that high variation in the mechanical strength can be noticed by changing in the level of each processing parameters. Very few studies have been made on the investigation of the effect of processing parameters on mechanical properties under cyclic loading conditions. For example, Arivazhagan et al [8] examined the influence of built style, road width, and raster pattern on the dynamic mechanical performance of polycarbonate manufactured part. Arivazhagan et al [9]conducted similar study on the effect of FDM operating conditions but on the part made by ABS material. In both studies, they conducted their experiments based on the trial and error approach. Their results indicated that the maximum dynamic performance can be obtained by using solid build style, 45° raster pattern and 0.454 mm road width.

Although during last decade a remarkable progress has been made in FDM process parameters optimization technique, but most of the existing literature focused only on improving the mechanical properties under static leading conditions. In fact, the parts manufactured by the FDM process are also subject to vibratory and cyclic conditions for long-term prediction with wide range of temperatures. There are two studies done so far on dynamic mechanical properties. However, they are expensive due to the use of one-factor-at-a-time (OFAT) method as well as they are limited in terms of the number of processing parameters being investigated and type of dynamic mechanical property observed. OFAT method cannot lead to optimal process settings and the relationships between the processing conditions and dynamic mechanical response using this approach are still unclear.

This paper differs from all previous studies in several ways. Firstly, unlike previous studies, which focused on the effect of FDM processing parameters on the static mechanical properties of the manufactured parts, this study examines the effect of FDM process conditions on the dynamic mechanical properties that resulted in understanding the material behaviour under cyclic loading conditions. Secondly, unlike most previous studies that aimed at investigating the influence of only few FDM process parameters, this paper considers the effect of six FDM processing parameters including a new variable – number of contours – which was not studied in the published literature before. Finally, unlike most previous studies, this study explores whether there is a significant relationship between the FDM process parameters and dynamic mechanical property, namely dynamic modulus of elasticity using fraction factorial design, regression analysis and artificial neural network (ANN). Results show that optimal process parameters lead to achieve desired dynamic modulus of elasticity of FDM produced part. Results obtained from this study would be useful for industry application and would help to produce the end user products with desired dynamic mechanical properties. It also can be used as a guide for planning and carrying out future studies.

2. Materials and methods

The experiments in this study were designed and performed using fraction factorial design. Fraction factorial design experimental design is commonly used to determine the most critical factors in the early stages of experimental work, when several process parameters are likely to be investigated as well as when the knowledge about the process is usually unavailable[10, 11]. This study used the stipulated conditions according to the fraction factorial design to plan the experiments. A total of 16 experiments were conducted at two levels of each input parameter. Two level fraction factorial experiment involves an experimental design in which each parameter is investigated at two levels. The early stages of experimental work and investigation usually involve the study of a large number of parameters to determine the vital parameters important for the system. Two level fraction factorial design is used in these stages to find out unnecessary factors so that attention can then be made only on the critical factors. The data were analysed using STATISTICA software. The experimental design used in this study considered the following processing parameters to investigate their effect on the dynamic modulus of elasticity; layer thickness (A), air gap (B), raster angle (C), build orientation (D), road width (E) and the number of contours (F). The selected process parameters and their levels are presented in Table 1 and they are selected according to the previous studies and FDM machine manufacturer (Stratasys) guide. The FDM build parameters are presented in Fig. 1.

Table 1 FDM process parameters and their levels

Factors	Units	Code	Levels	
			Low	High
Layer thickness	mm	A	0.127	0.3302
Air gap	mm	B	0	0.5
Raster angle	deg	C	0	90
Build orientation	deg	D	0	90
Road width	mm	E	0.4572	0.5782
Number of contours	-	F	1	10

A total of 16 samples having dimension of 35 (length) mm × 12.5 mm (width) × 3.5 mm (thickness) were fabricated by FDM Fortus 400 as per designed plan presented in Table 2 and tested according to ASTM D5418 [12] and TA instrument manufacturer recommendations [13]. All samples are made by PC-ABS material which has amorphous structures. Dynamic modulus of elasticity is a viscoelastic property that exhibit both viscous and elastic behaviors which is present in the material or manufactured part during undergoing deformation. It is the ratio of peak dynamic stress to peak dynamic strain under vibration and harmonic loading. Therefore, dynamic modulus of elasticity measures the sample and material resistance to deformation [14].

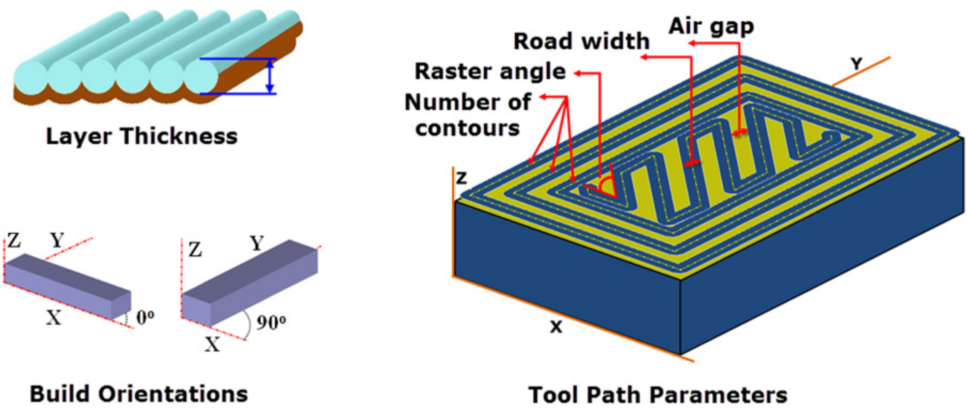

Fig. 1 FDM build parameters

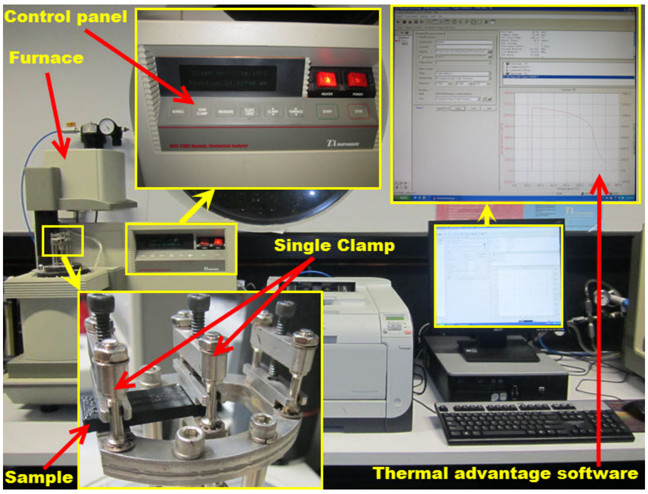

Fig. 2 Schematic illustration of dynamic mechanical test

The dynamic mechanical response in terms of dynamic modulus of elasticity of the 16 samples was measured using 2980 Dynamic Mechanical Instrument in the bending mode with single cantilever. Dynamic mechanical measurement was done with single frequency of 1 Hz with a heating rate of 3 °C /min, oscillation amplitude of 15 µm, and the temperature ranges between 35-170 °C with soaking time of 5 min. The stress-strain curve, which was generated by dynamic mechanical machine and analysed by Thermal Advantage Software, has been used to determine the maximum dynamic modulus of elasticity for each experimental run according to fraction factorial design matrix plan. The average of the maximum values of dynamic modulus of elasticity was taken from a set of tested samples. The experimental design plan in terms of coded parameter with the measured dynamic modulus of elasticity is presented in Table 2.

Table 2 Experimental design matrix

Run	A	B	C	D	E	F	Dynamic modulus of elasticity (MPa)
1	0.127	0.5	90	0	0.4572	1	4.255
2	0.127	0.5	90	90	0.4572	10	11.028
3	0.127	0	90	0	0.5782	10	12.339
4	0.127	0	0	90	0.4572	10	12.946
5	0.127	0.5	0	90	0.5782	1	5.542
6	0.127	0.5	0	0	0.5782	10	13.056
7	0.127	0	90	90	0.5782	1	10.881
8	0.127	0	0	0	0.4572	1	12.228
9	0.3302	0.5	90	0	0.5782	1	4.732
10	0.3302	0	90	0	0.4572	10	14.287
11	0.3302	0	90	90	0.4572	1	12.829
12	0.3302	0.5	0	90	0.4572	1	4.240
13	0.3302	0	0	90	0.5782	10	12.771
14	0.3302	0.5	90	90	0.5782	10	11.504
15	0.3302	0	0	0	0.5782	1	12.054
16	0.3302	0.5	0	0	0.4572	10	11.753

3. Results and discussion

The relationships between measured dynamic modulus of elasticity and the FDM process parameters were developed by fitting the data in a two-factor interaction (2FI) model presented in Eq. 1, where, Y is the predicted response (dynamic modulus of elasticity), β_0 is a constant intercept, β_i is the coefficient for the linear terms, β_{ij} is the interaction coefficient, X_i and X_j are the coded factors, and and ε is the random error term.

$$Y = \beta_0 + \sum_{i=1}^{6} \beta_i X_i + \sum_{i<j}^{6} \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

The ANOVA technique was employed to test the significance of the main effects and the two-factor interaction effects for maximum dynamic modulus of elasticity. The experimental results for maximum dynamic modulus of elasticity in relation to process parameters are shown in Fig. 3(a) using half-normal plot (α = 0.05). For each of the F test (Fisher's test) 0.05 level of significance is used to analyze the data obtained from factorial design experiment. Typically, the higher value of F-ratio indicates higher impact of that factor on the dynamic modulus of elasticity. Backward elimination of insignificant effects was applied. Insignificant linear terms were included in the regression model if they have significant interaction effect with other main effect. The correlation coefficient (R^2) is used to measure how well the developed model accurately represents the experimental data. The R^2 value is between 0 % and 100 %. It is clear from ANOVA result presented in Table 3 that the values of R^2 (98.38 %), adjusted R^2 (97.30 %) and predicted R^2 (94.89 %) are considerably high and hence the developed regression model fits the experimental data well. The final developed regression model for dynamic modulus of elasticity (in MPa) is presented in Eq. 2:

$$Dynamic\ modulus\ of\ elasticity = 12.879 - 3.634A - 15.957B - 0.028C + 0.121F + 0.107AC + 1.346BF \quad (2)$$

It can be concluded from Fig. 3(a) that the points which are located away from the fitted line indicate the significant model terms for dynamic modulus of elasticity. Findings from this plot confirmed that the air gap (B), number of contours (F) and their interaction have a significant influence on dynamic modulus of elasticity. However, layer thickness (A) is not a significant factor, but its interaction with raster angle (C) has a strong influence on dynamic modulus of elasticity. The assumptions can be tested and checked through the normal probability plot. The normal probability plot presented in Fig. 3(b) shows that the experimental data fall linearly close to the fitted line, which demonstrates that the model perfectly describes the population data.

Fig. 4(a) shows the predicted values versus the actual values plot. This plot shows that the fitted values of response are in high correlation with the actual values, which demonstrates an adequate signal for regression model. Fig. 4(b) represents the externally residual versus run number order of dynamic modulus of elasticity. It is clear from Fig. 4(b) that there are no outliers found in the residuals plot. All residuals are consistently distributed along the run number. Fig. 4(c) shows leverage versus run number to ensure that no run has high value of leverage which may affect the model. This figure shows that all runs are fitted exactly with no residual and with no high leverage.

Table 3 ANOVA results

Source	Sum of squares	Degree of freedom	Mean square	F- Value	Prob > F
Model	182.11	6	30.35	91.25	< 0.0001
A	0.22	1	0.22	0.67	0.4327
B	73.21	1	73.21	220.09	< 0.0001
C	0.47	1	0.47	1.40	0.2664
F	67.75	1	67.75	203.67	< 0.0001
AC	3.80	1	3.80	11.44	0.0081
BF	36.66	1	36.66	110.22	< 0.0001
Residual	2.99	9	0.33	-	-
Total	185.11	15	-	-	-

R^2 = 98.38 %, Adjusted R^2 = 97.30 %, Predicted R^2 = 94.89 %, Adequate precision = 25.454

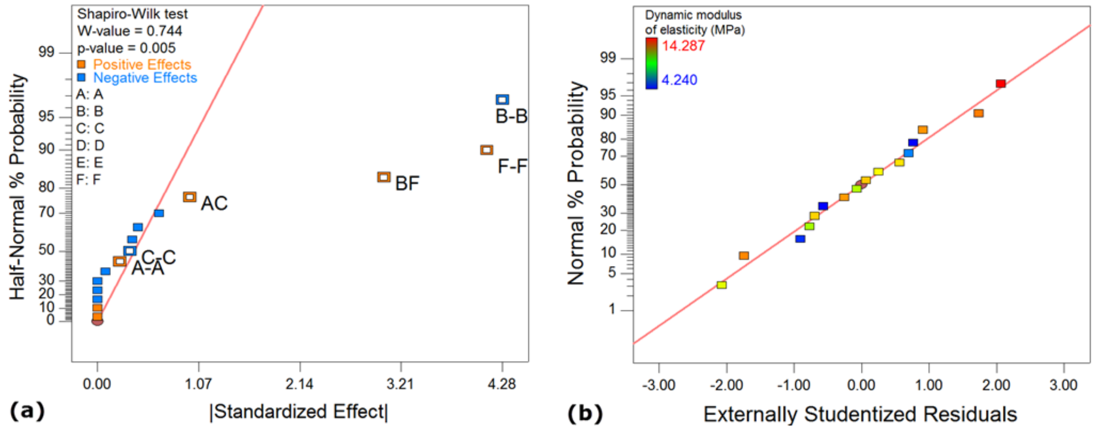

Fig. 3 (a) half normal probability plot of the standardized effects, and (b) normal probability plot, for dynamic modulus of elasticity

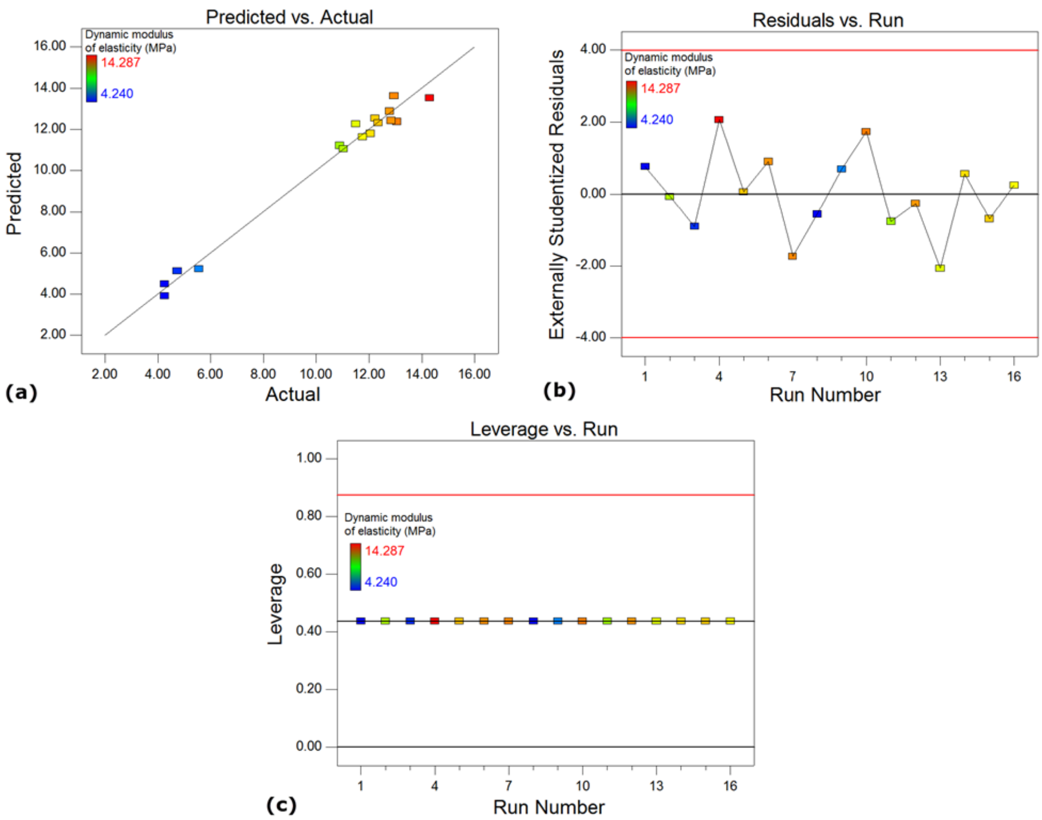

Fig. 4 (a) predicted versus actual plot, (b) residual versus run number plot, and (c) leverage versus run number plot

Effect of layer thickness (slice thickness) on the dynamic modulus of elasticity of the parts can be seen in Fig. 5. With the increase in slice thickness, dynamic modulus of elasticity of the part slightly increased. It is because as the layer thickness increases, it produces thick rasters with minimum number of layer. This leads to the improvement in dynamic mechanical properties of the built part. Nevertheless, if the part is fabricated with thin layers, there would be micro-voids and tear in a part surface (see Fig. 6). Thus the sample processed with thin layers exhibits lower mechanical performance. Fig. 5 reveals the influence of air gap on the dynamic modulus of elasticity. It is found that with an increase in air gap, dynamic modulus of elasticity decreases gradually. The main reason is that when the air gap increases, a close raster and deposited beads are generated, which leads to a dense structure resulting in improvement in dynamic modulus of elasticity of parts.

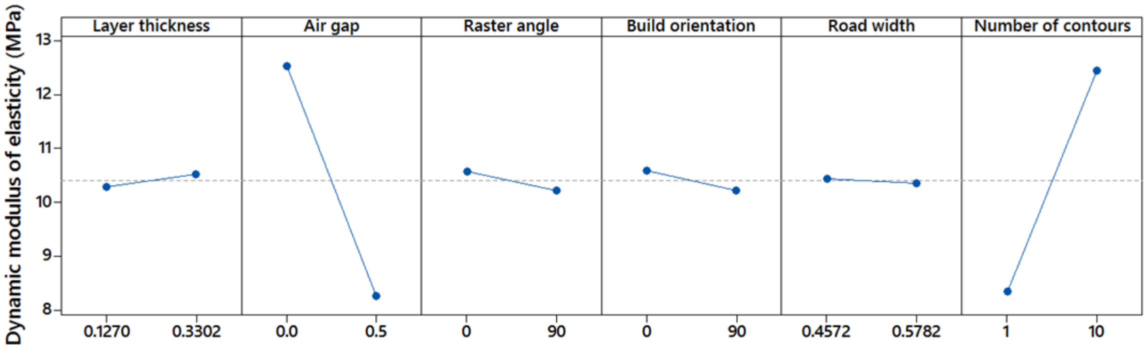

Fig. 5 Effect of various operating conditions on dynamic modulus of elasticity

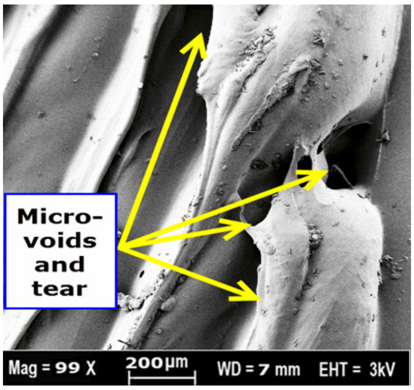

Fig. 6 Microstructure observation of the effect of thin layer on the properties of the manufactured part

Fig. 5 also shows the impact of raster angle (raster pattern) on the dynamic modulus of elasticity on the samples built through FDM. It has been observed the dynamic modulus of elasticity for the manufactured part decreases with increasing raster angle from 0° to 90°. The main reason behind this phenomenon is that when the raster angle increases, the energy absorbed by the manufactured part decreases. This is due to the fact that at raster angle of 90° an adhesive failure occurs at the bonding interface level of the deposited layers (see Fig. 7). This leads to reduction in the dynamic modulus of elasticity of the processed part. Fig. 7 clearly shows the phenomena behind the influence of two raster's angles on the dynamic modulus of elasticity.

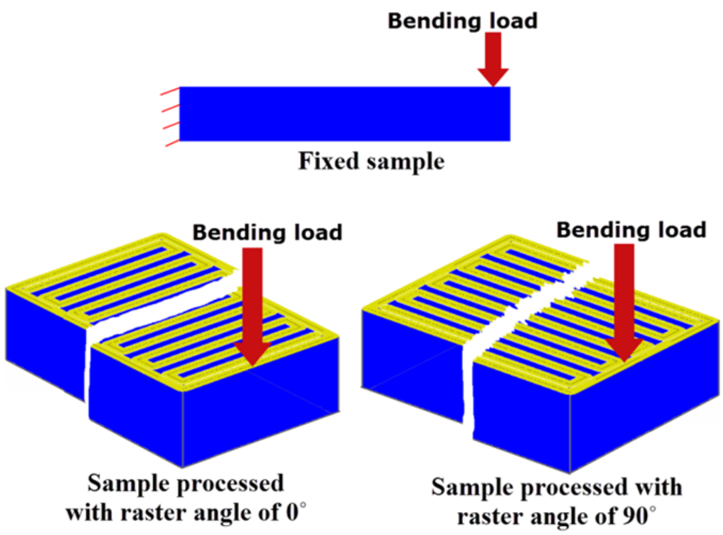

Fig. 7 Failure of different rasters under periodic bending load

The effect of build orientation on dynamic modulus of elasticity is illustrated in Fig. 5. To acquire high deformation resistance for the fabricate part, it is preferable to manufacturing the part along the X-axis (0°) as this can greatly improve the curve definition for rasters, and can decrease stair-stepping effect. Fig. 5 indicates that the road width has no effect on the dynamic modulus of elasticity. Thus this factor has been removed from the regression model expressed which is by Eq. 2. However, in general it is advisable to use thin road width as thin road width provides finer raters and layers, which helps in filling more spaces on the part structure. Thus the built parts tend to have better mechanical properties, better dimensional accuracy and improved surface roughness. The effect of number of contours on dynamic modulus of elasticity is shown in Fig. 5. The results indicate that higher values of dynamic modulus of elasticity can be obtained by considering 10 contours. The maximum contour lines can guarantee elevated absorb and discharge energy levels and help the part to return to its original position after the stress is released. Because the reason for this improvement is maximum number of contours reduces the number of rasters, which helps to create the solid and dense structure (see Fig. 8) and hence increases the dynamic modulus of elasticity.

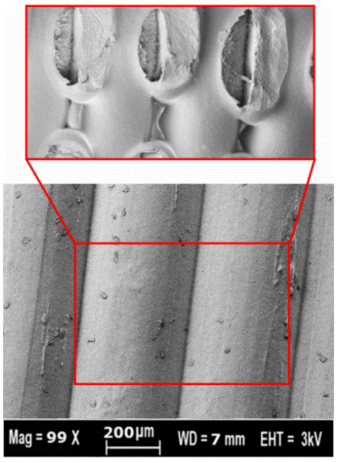

Fig. 8 Microstructure observation of the effect of 10 contours on the properties of the manufactured part

Fig. 9 portrays the dual influence of air gap and number of contours on dynamic modulus of elasticity at a constant level of the other processing parameters. It can be concluded that maximum dynamic modulus of elasticity is feasible with a combination of low air gap and higher number of contours. However, an interesting phenomenon can be noticed from Fig. 9 that using highest value of air gap along with maximum number of contours higher dynamic modulus of elasticity can still be obtained. This is because the part still has solid structure under this parametric combination, and hence this combination of process parameters helps to improve the mechanical properties while reducing the production cost as positive air gap minimizes the processing time.

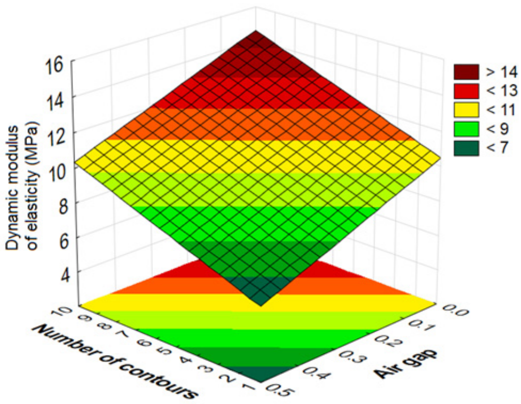

Fig. 9 Combined effect of air gap and number of contours on dynamic modulus of elasticity

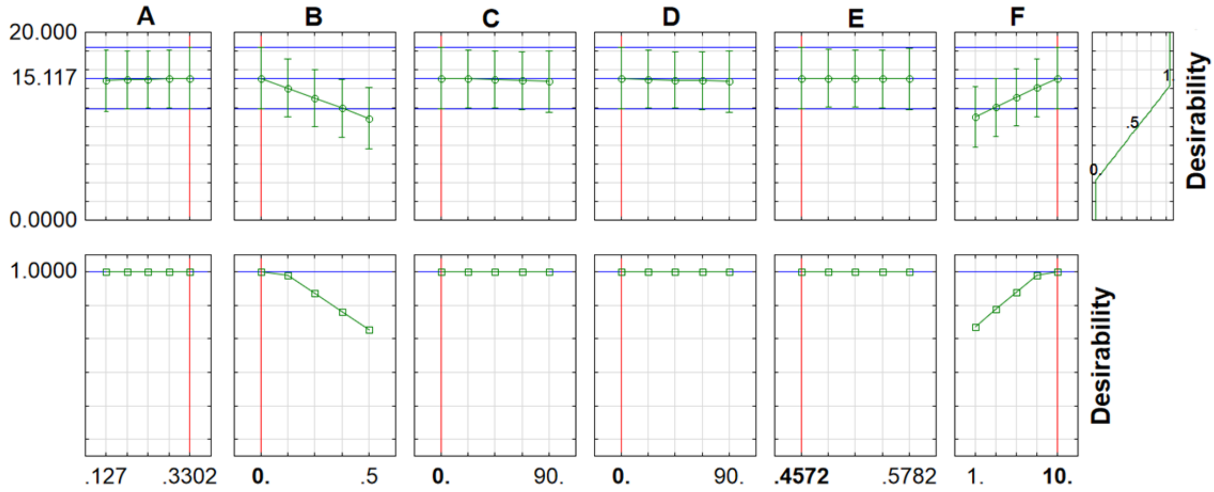

Fig. 10 Optimization results

Process optimization was conducted to find the optimal parameter setting to maximize dynamic modulus of elasticity of the part. In this investigation the search-based optimization process described by Derringer function has been used. Accordingly, the optimal parameter setting to optimize the dynamic modulus of elasticity of the part is presented in Fig. 10. Overall, it can be concluded that the optimal parameter setting is: A = 0.3302 mm, B = zero air gap, C = 0°, D = 0°, D = 0.4572 mm and F = 10. Confirmation experiment was also done at the predicted dynamic modulus of elasticity under the optimal parameter setting. The results from the confirmation experiment has shown that maximum dynamic modulus of elasticity of 14.6289 MPa was obtained, which is in a very good agreement with the predicted value of 15.117 MPa.

The desirability index for each of the parameter combination obtained for each experimental run presented in the design matrix of Table 2 was determined in order to compare each desirability index for each experimental run with the optimal process parameter (Fig.10). This helps us to understand how each set of parameter combination in experimental design matrix in Table 2 satisfies the dynamic modulus of elasticity. It can be noticed from Fig. 11 that the optimal process parameter presented in Fig. 10 has the highest desirability index of 1. This indicates that the optimal process parameter is highly desirable for achieving a high dynamic modulus of elasticity of FDM fabricated part.

For comparison purpose, the data used for the optimization of dynamic modulus of elasticity by fractional factorial design has also been used for optimization by artificial neural network (ANN) based on multilayer perception (MLP). In this case, the K-fold cross-validation neural network was used, as it is the best method for small data sets. This is due to the fact that it makes an efficient and accurate use of limited data. The K-fold cross-validation method divides the experimental data into K subgroups. Each of the K sets is then used to validate the prediction and model fit is done on the rest of the experimental data. The model provides the highest coef-

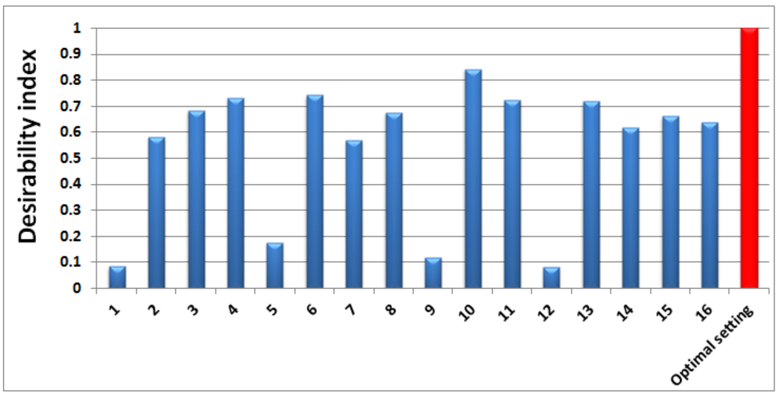

Fig. 11 Desirability index for experimental runs and the optimal process setting

ficient determination (R^2) and the lowest selection error is selected as the final model. Fig. 12 shows schematic diagram of ANN used in this study. It was observed that the optimal number of neurons in the hidden layer is 3 (MLP 6-3-1) with an observed training performance of 99.92 % and a root mean squared error (RMSE) of 0.093 as shown in Table 4.

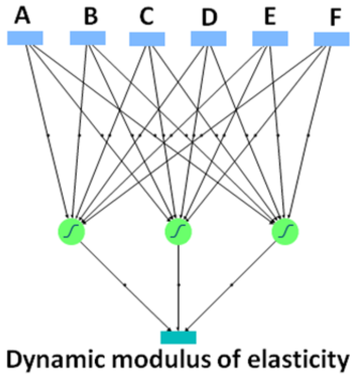

Fig. 12 Schematic diagram of developed ANN model

Table 4 Training and validation results of ANN model

Training		Validation	
Measures	Value	Measures	Value
R^2	99.92391 %	R^2	89.43943 %
RMSE	0.0926835	RMSE	1.0694804
Mean absolute deviation	0.0434715	Mean absolute deviation	0.9250841
-Log likelihood	-9.596264	-Log likelihood	8.916669
SSE	0.0859023	SSE	6.8627305
Sum frequency	10	Sum frequency	6

The predicted values obtained by ANN and fractional factorial model are compared and illustrated in Fig. 13. The results demonstrate that ANN model is slightly better than the fractional factorial model. Results indicate that the ANN model prediction line is much closer to the line of experimental data than the fractional factorial model. The higher performance and accuracy of the ANN can be attributed to its ability to determine the nonlinearity of relationships of the process, while the fractional factorial is restricted to a two-factor interaction (2FI) polynomial.

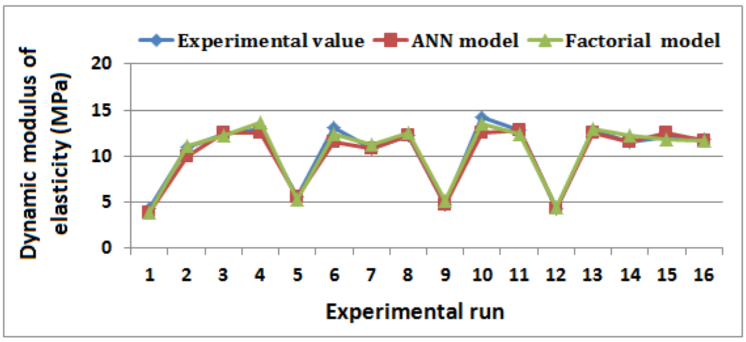

Fig. 13 An illustration of model comparison between predicted values and actual values of ANN and fractional factorial models for dynamic modulus of elasticity

4. Conclusion

In this study, dynamic modulus of elasticity of PC-ABS parts made by FDM was investigated using fraction factorial design. Since no study has been found in the literature review on the effect of processing parameters on dynamic modulus of elasticity of the manufactured parts by FDM, this study can provide important information to guide the future researches. On the basis of the results achieved from this work, the following conclusions can be made:

- With increasing the layer thickness there is a marginal improvement in dynamic modulus of elasticity of the parts. This is due to the fact that thick layers lead to minimum number of layers, which consistently improve the deformation resistance of the manufactured part by the FDM process.
- With the increase in the contour lines there is a continuous improvement in dynamic modulus of elasticity of the manufactured parts. The reason is number of contours reduces the number of rasters, which helps to minimize the porosity in the processed part.
- On the contrary, with increase in air gap, raster angle, build orientation and road width, there is a decrease in dynamic modulus of elasticity of built parts.
- Positive value of air gap is not desirable as it makes the part less dense.
- Lowest value of raster angle is preferred as it produces less number of rasters.
- Building the part at X-axis (0°) can improve the curve definition for rasters, and can minimize the stair-stepping effect.
- It was noticed that minimum road widths give slightly better properties as minimum road width creates finer and thin rasters and layers, which fills more spaces on the part structure.
- Maximum dynamic mechanical performance in terms of dynamic modulus of elasticity can be achieved using optimized operating parameter setting: A = 0.3302 mm, B = zero air gap, C = 0°, D = 0°, E = 0.4572 mm and F = 10. Results obtained from this study would help to manufacture the end user products with better dynamic mechanical performance.
- The ANN model was found to have greater predictive capability of dynamic modulus of elasticity of built parts in comparison to the fractional factorial model in terms of the coefficient of determination (R^2) and the absolute average deviation even with limited number of experiments.
- The limitation of this study is that all process parameters were studied only at two levels. Therefore, number of levels should be increased in future work so that more accurate response of the manufactured part in relation to process parameters can be assessed.

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APEM journal
Advances in Production Engineering & Management
Volume 11 | Number 3 | September 2016 | pp 239–250
http://dx.doi.org/10.14743/apem2016.3.224
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Tool wear and cost evaluation of face milling grade 5 titanium alloy for sustainable machining

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ABSTRACT

Cutting tool life, its wear rate and machining cost play significant role in a machining process. Effect of these parameters using face milling of titanium alloy is analysed to assess the economic factor of sustainability. Machining sustainability of Ti-6Al-4V hardened to 55 HRC is assessed through a novel technique of iso-response method, in which the response value, i.e. surface finish is taken as criteria for evaluation and comparison among dry, conventional and cryogenic machining. Experiments are designed in DOE for central composite design and performed face milling of Ti-6Al-4V with PVD coated carbide inserts using three conditions of cooling and measured the response values. Feed, speed, and depth of cut were used as input variables. Comparing the average results of tool life and machining cost for iso-response technique, it was found that 47.55 % less electricity cost and 47.59 % less machine operating cost and 10.76 times increased cutting tool life achieved for cryogenically cooled experiments as compared with dry machining. Coolant cost was found 13.33 times cheaper for cryogenic as compared with conventional machining. The results indicate that cryogenic cooling is more sustainable for tool life, having better surface finish of machined part with least energy and machining cost.

ARTICLE INFO

Keywords:
Titanium alloy
Milling
Sustainable machining
Machining cost
Tool life

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Article history:
Received 12 April 2016
Revised 15 August 2016
Accepted 23 August 2016

1. Introduction

In machining of difficult-to-machine materials like Ti-6Al-4V, excessive tool wear and heat are produced making the surface quality poor [1]. Alternative solutions of dissipating the heat generated at chip-tool interface and cutting tool materials is in exploration since last few years. Main reasons for rapid tool wear are building of high cutting temperatures. Cost of a machined part mainly involves the cost of cutting tools, electrical energy, labour and coolant cost. High machining cost of titanium alloy Ti-6Al-4V has made it important to ensure longer tool life by selecting the favourable cutting conditions [2]. Bulk use of conventional coolant in machining industries is causing increase in environmental damage [3]. Trends are shifting from conventional to sustainable manufacturing due to increase in occupational diseases of workers and need for reduction in overall manufacturing cost [4]. For implementation of cryogenic machining at industrial level, investigations are required about the tool wear and tool life using cryogenic cooling [5]. Nowadays, machining industries are forced to adopt the manufacturing processes which are environment friendly. The objectives of this research work are to identify the effect of cryogenic cooling over tool wear and tool life for face milling of hardened Ti-6Al-4V, machining cost evaluation for dry, conventional and cryogenic cooling and identification of alternate cooling technique for sustainable machining. The results show that using cryogenic cooling, cutting tool life is enhanced and machining cost is reduced as compared with dry or conventional machining. A novel technique of iso-response method is introduced which is helpful in evaluation of machining sustainability.

2. Literature review

Sustainability achievement of difficult-to-machine materials is major concern now-a-days. Industrial trends are shifting from conventional to sustainable manufacturing principles. Such revolutions are outcome of diseases found in workers at shop floor, requirement of cost reduction for manufacturing and government policies for environmental protection [4]. Cutting fluids are dangerous to health and environment as found in presently performed investigations [6]. In a report it is stated that about 80 % of the skin diseases are due to the use of cutting fluids [7]. European union estimated for metal working fluid and found that 320,000 tons of it annually used and 66 % of which is disposed-off after usage [8]. Coolants used in cryogenic cooling are safe for workers and environment as compared with conventional coolants. The air consists of 79 % of nitrogen gas which is extracted and compressed to liquid nitrogen, which has no hazards for work's life; therefore can be used as cooling medium in cryogenic machining. Using N_2 gas as cooling medium has many advantages such as tool life enhancement, improvement of surface integrity, productivity improvement, reduction of build-up-edge, increasing chip breakability and reduction in burr formation [9, 10]. Alternates of cutting fluid like N_2, O_2 and CO_2 have been used and compared to wet and dry machining and found that fine surface finish obtained with increased flow rates and pressure of gases [11]. End milling of Ti-6Al-4V using liquid nitrogen, conventional cooling (flooded) and dry machining performed to check surface roughness, microscopic surface integrity, subsurface micro-hardness and found that using cryogenic cooling 39 % and 31 % lower surface roughness achieved when compared to dry and flood cooling methods [5]. Turning of stainless steel was assessed for sustainability using minimum quantity solid lubricant in comparison with dry, wet and minimum quantity lubrication technique and found reduction in tool wear with improved surface finish [12]. Sustainability is needed to be incorporated in all steps of the manufacturing.

Machining is one of the mostly used processes in developing a product. By involving the sustainability principles into machining process, the economic and health sectors can be improved in order to get saving in cost and enhanced environmental performance. Machining process contributes to worldwide economy therefore oil based coolants are generally not recommended as cooling and lubrication fluid (CLF) as they tend to make the machining process unsustainable. These coolants are formulated from mineral oil which is extracted from highly non-sustainable crude oil. Vegetable oils are not used as cooling and lubrication fluid due to their reduced performance and higher cost [13].

Cost of machining is a major element of a mechanical industry. Cutting tools having long tool life are preferred over those with short tool life in order to reduce overall machining cost and increasing productivity. A cost estimation model has been proposed in [14] for optimization of machining cost which includes material cost, tool cost, overhead and labour cost; in this proposed model if the desired cost effective results are not achieved then the feedback is given to designer for modifications. The feasible process parameters including cutting speed, feed rate and depth of cut are selected to attain optimum results. Constraints of cutting tool specification, tolerances, cost, time, machining sequence and required surface finish are taken into consideration. Machining of inconel 718 considered for evaluation of sustainability parameters and found that cryogenic machining is more sustainable for machining cost, energy cost, resource consumption, machining cost, CLF cost, waste processing cost, total production cost and part production cost as compared with conventional [15, 16].

It is important to cool down the cutting tool temperature in order to improve the cutting tool life, especially in the case when machining the materials with low thermal conductivity like titanium Ti-6Al-4V [17]. Using the cooling technique of minimal quantity lubrication (MQL), it was found that tool wear is decreased, life of cutting tool is increased and the quality of surface finish was improved as compared the results with conventional and dry machining [18]. Development in lubrication techniques and coolants has a lot of gap for researchers to find optimal cooling systems. In reports it is given that tooling cost is about 4 % of the total machining cost and coolant/lubrication cost is about 15 % of total machining cost [19], therefore huge sustainability gain is possible by avoiding CLF and using high performance coated cutting tools [20]. Reduction in size of chip build up edge and tool wear found in turning of Ti-6Al-4V using cryogenic compressed air [21]. Cryogenic cooling done to study machinability and tool wear effect in end milling of titanium Ti-6Al-4V using coated carbide cutting tools and found that tool wear was slowed down and surface roughness reduced by 11 % and 59 % as compared with dry and wet conditions [22]. Liquid nitrogen used for turning of composite material and found sustainable in reducing surface roughness, tool wear and cutting temperature [23]. Growth of flank wear was significantly reduced by using liquid nitrogen in turning of Ti-6Al-4V [24]. More improvement in tool life and surface integrity was found using cryogenic machining of inconel 718 as compared with conventional [25]. Flank wear, surface finish, cutting power calculated at different combinations by turning Ti-6Al-4V with dry, flood cooling, vegetable oil, cooled air lubrication, cryogenic with LN_2 and vegetable oil mixed with cooled air and it was found that vegetable oil is more sustainable at feed 0.1 mm/min and speed 90 m/min [26]. Cutting forces, machining temperatures, tool wear, machined surface quality, chip formation and energy consumption investigated using end milling of inconel 718 carried under dry, conventional and cryogenic cooling and found that cryogenic cooling is promising for machinability and sustainability improvement as compared to conventional and dry [27].

Presently most of the work reported on sustainable machining of Ti-6Al-4V generally addresses the issue using material in annealed form. In some applications parts are machined after hardening Ti-6Al-4V. Sustainability issue for such condition needs more exploration.

3. Experimental results

Face milling of titanium alloy Ti-6Al-4V was performed in three different conditions of dry, conventional and cryogenic cooling. Initially the alloy was heat treated up to hardness of 55 HRC. DMU-50 CNC milling machine used for face milling with PVD coated carbide inserts "APTM 1135 PDER-M2 VP15TF". Specific values of feed, speed and depth of cut were selected and response of surface finish was checked using perthometer M2 with drive unit Mahr PGK-120. Three levels of cutting speed 20 m/min, 35 m/min and 50 m/min, feed levels of 0.1 mm/tooth, 0.15 mm/tooth and 0.2 mm/tooth, depth of cut having levels of 0.05 mm, 0.1 mm and 0.15 mm were selected. Experiments were designed in RSM for central composite design technique using Design Expert 7.0.0 software. Response values of surface finish were measured for each experiment as shown in Table 1.

3.1 Tool life comparison

The Taylor's tool life equation as given in Eq. 1 used to calculate the cutting tool life. This equation deals in finding tool life for fixed feed and depth of cut.

$$VT^n = C \tag{1}$$

Where n is a constant based on tool material and C is a constant based on tool & work. Value of C expresses the cutting speed of a tool for one minute of tool life. Taking value of C 300 for dry, 507 for conventional and 1142 for cryogenic conditions [28] and value of n taken as 0.5 specified for carbide cutting tools. Tool life calculated for each value of cutting speed V, and is shown in Table 1. Nearly common response values of surface roughness were selected for further comparison of tool life, machining cost calculations and sustainability evaluation using dry, conventional and cryogenic cooling.

Comparison of tool life for all experimental runs of Table 1 is shown graphically in Fig. 1. It describes that the tool life is highest for cryogenic cooling as compared to dry and conventional.

For carrying out further analysis, common response values of R_a and comparison with the tool life is performed which is given in Table 2.

Table 1 Experimental input values, measured response values and calculated tool life

Exp. No.	Input variables			Surface roughness, (R_a) µm			Tool life, min		
	Cutting speed (m/min)	Feed, f_r (mm/min)	Depth of cut (mm)	Dry	Conv.	Cryogenic	For dry	For conv	For cryo
1	20	63.662	0.050	0.89	1.996	0.519	225	643	3260
2	50	159.155	0.050	0.95	1.98	0.569	36	103	522
3	35	167.113	0.016	0.991	1.187	0.63	73	210	1065
4	35	73.530	0.100	0.763	0.681	0.362	73	210	1065
5	35	167.113	0.100	1.727	1.078	0.947	73	210	1065
6	35	167.113	0.100	1.354	1.188	0.3	73	210	1065
7	35	167.113	0.100	1.321	1.349	0.383	73	210	1065
8	35	167.113	0.100	1.195	1.301	0.447	73	210	1065
9	60.227	287.563	0.100	1.61	1.578	1.5	25	71	360
10	20	63.662	0.150	1.043	0.289	0.37	225	643	3260
11	50	159.155	0.150	1.073	0.431	0.339	36	103	522
12	20	127.324	0.050	1.62	0.929	0.5	225	643	3260
13	50	318.310	0.050	1.77	0.587	0.684	36	103	522
14	50	318.310	0.150	2.198	0.929	0.557	36	103	522
15	20	127.324	0.150	2.151	0.853	0.63	225	643	3260
16	35	260.696	0.100	1.916	2.738	2.348	73	210	1065
17	35	167.113	0.184	1.606	1.823	0.905	73	210	1065
18	35	167.113	0.100	---	1.02	0.946	73	210	1065
19	35	167.113	0.100	---	0.98	0.975	73	210	1065

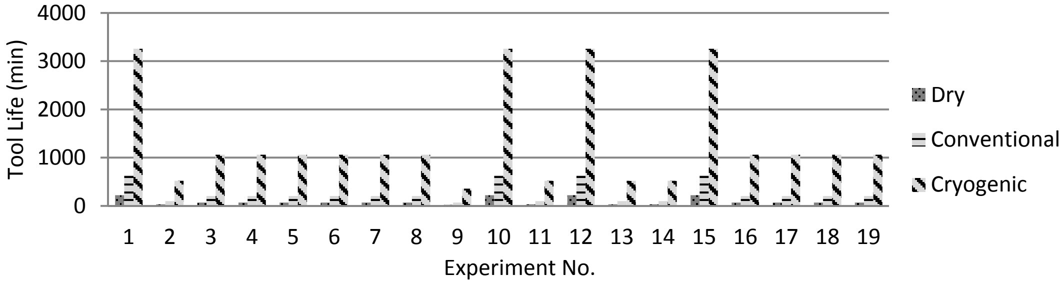

Fig. 1 Comparison of tool life for dry, conventional and cryogenic cooling

The graphical comparison of tool life is given in Fig. 2, and is evident from the comparison of tool life that using cryogenic cooling, the cutting tool will last for more machining time than for conventional and dry. The surface finish obtained is nearly same for these combinations of speed, feed and depth of cut using different cooling combinations however the tool life is greatest in cryogenic conditions.

Table 2 Tool Life for experimental runs having nearly identical R_a

Combination No.	Response, R_a (µm)			Tool life (min)		
	Dry	Conventional	Cryogenic	Dry	Conv	Cryo
1	0.89	0.853	0.905	225	643	1065
2	0.95	0.929	0.947	36	103	1065
3	1.073	1.078	0.975	36	210	1065
			Average	99	318.6	1065

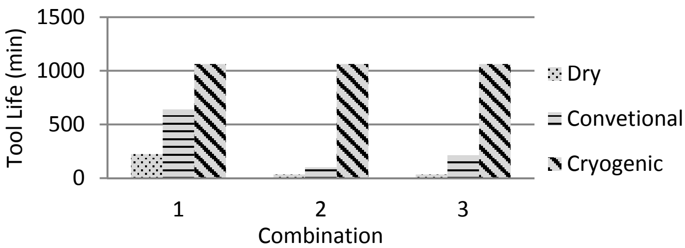

Fig. 2 Tool life comparison based on iso-response values

3.2 Machining cost calculations

Total machining cost (C_m) comprises of multiple associated costs including electricity cost (C_e), overhead cost (C_{oh}), cutting tool inserts cost (C_t) and wasted lubricant/coolant cost (C_{cw}). These calculations are made to compare the cost for selected common response values (R_a) as given in Table 3. Total machining cost in cumulative form can be represented by Eq. 2.

$$C_m = C_e + C_{oh} + C_t + C_{cw} \tag{2}$$

Electricity cost

The electricity cost calculated using Eq. 3.

$$C_e = C_p \times \frac{P_m}{\eta_m \times 60} \times T_m \tag{3}$$

where C_p is unit energy price in PKR/KWh (20 PKR/KWh at working site), P_m is power of machine in KW (power by main motor and power by coolant pump), η_m is machine efficiency, and T_m is machining time in minutes.

Machine cutting time T_m is calculated using expression of Eq. 4 where cutting length ($L+A$) taken as 100 mm and value of f_r taken from Table 1. Calculated values of machining time (T_m) are given in Table 3.

$$T_m = \frac{L + A}{f_r} \tag{4}$$

Table 3 Machine cutting time for iso-response values of R_a

Combination	Dry		Conventional		Cryogenic	
	R_a (μm)	T_m (min)	R_a (μm)	T_m (min)	R_a (μm)	T_m (min)
1	0.89	1.571	0.853	0.785	0.905	0.598
2	0.95	0.785	0.929	0.314	0.947	0.598
3	1.043	1.571	1.019	2.143	0.946	0.598
4	1.073	0.628	1.078	0.598	0.975	0.598

Eq. 3 has been used for calculating cost of electricity. Here it is notable to mention that the cooling pump is used only in conventional machining so its power consumption is added in calculations. Value of main motor power is 15 KW and power of coolant pump is 0.27 KW. Value of mechanical efficiency (η_m) taken as 0.9 therefore using the values, the electricity cost calculated as given in Table 4.

Fig. 3 shows the graphical comparison of electricity cost against iso-response values of R_a. It is evident that electricity cost is less for the cryogenic cooling as compared to conventional and dry. For second combination, the electricity cost for conventional is less whereas on average basis the electricity cost for cryogenic is less overall.

Table 4 Electricity cost comparison

Combination	Electricity cost, PKR		
	Dry	Conventional	Cryogenic
1	8.73	4.44	3.32
2	4.36	1.78	3.32
3	8.73	12.12	3.32
4	3.49	3.38	3.32
Average	6.33	5.43	3.32

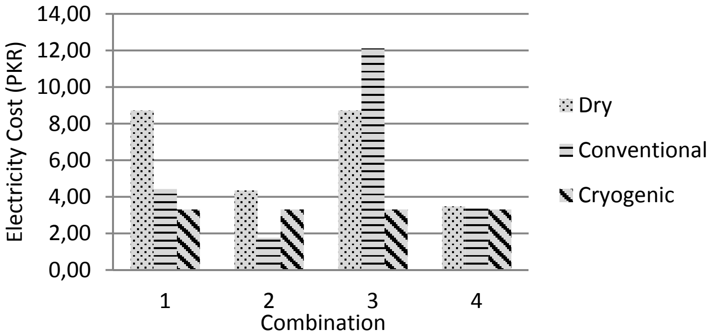

Fig. 3 Comparison of electricity cost

Overhead cost

Overhead cost (C_{oh}) comprises the sum of machine operating cost (C_o), HVAC/lighting cost (C_h) and machine depreciation cost (C_d) as given by following expression:

$$C_{oh} = C_o + C_h + C_d \tag{5}$$

Here machine operating cost will be calculated using Eq. 6.

$$C_o = C_{Lb} \times \sum_{i=1}^{n} Lb_i \times T_i \tag{6}$$

where C_{Lb} is labour unit cost in PKR/hr (208 PKR/hr), Lb_i is number of labours in i^{th} operation, T_i is process time in hours (for i^{th} operation).

By using the machining time from Table 3, the machine operating cost for selected iso-response values of R_a can be calculated as given in Table 5.

Table 5 Machine operating cost for iso-response values of R_a

Combination	Machine operating cost, PKR		
	Dry	Conventional	Cryogenic
1	5.45	2.72	2.07
2	2.72	1.09	2.07
3	5.45	7.43	2.07
4	2.18	2.07	2.07
Average	3.95	3.33	2.07

It is evident from Fig. 4, that the machine operating cost is less for cryogenic machining as compared with dry and conventional. For 2nd combination, the machine operating cost is less for conventional however on average basis, the machine operating cost is less for cryogenic cooling. Lightening, HVAC cost and machine depreciation cost is nearly same for all therefore their effect can be neglected for specific case.

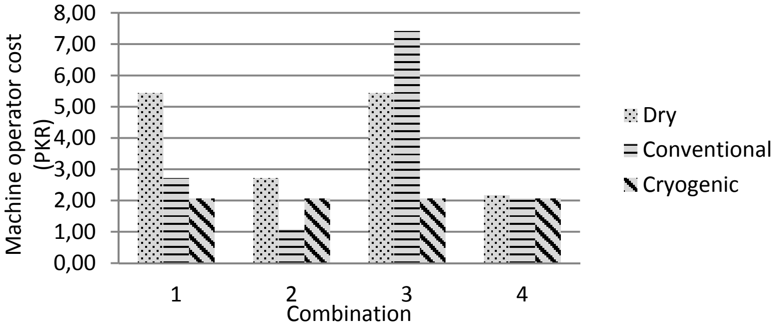

Fig. 4 Machine operating cost comparison

Cutting tool cost

Cost of a cutting tool insert (C_t) is PKR 500 (1US$=107 PKR). Cutting tool's cost is dependent upon the tool life. Shorter the tool life will need more tools in a complete operation. Considering data of tool life presented in Table 1 & Table 2 it is clear that minimum tool life is 36 min for dry, 103 min for conventional and 1065 min for cryogenic therefore the number of cutting tools will be higher for dry machining as compared with conventional and cryogenic. Here the cutting inserts cost was taken as for two inserts in each scenario.

The calculation of machining time is based on work piece length of 100 mm. As far as the work piece machining length will be increased, the machining time will also be increased accordingly, therefore requirement of cutting inserts will be increased for each scenario based on their tool life resulting that machining cost in dry machining will increase more rapidly.

Cost of wasted coolant

Coolant used in conventional machining is "Shell macron 221 CM-32" having cost (C_c) of 500 PKR per litre. Flow rate (Q_c), for coolant was measured as 3 litres per min. This coolant is re-used by circulating through pumping action and filtration system. Some of the coolant quantity is wasted in cleaning process which is taken as 0.05 litre per min. This wasted quantity (Q_w), has direct impact on cost burden in the calculation of coolant cost.

Therefore the cost of coolant wasted during machining (C_{cw}) is calculated using Eq. 7 and is given in Table 6.

$$C_{cw} = C_c \times Q_w \times T_m \tag{7}$$

For cryogenic machining, the cost of liquid nitrogen is 6 PKR per litre. The estimated consumption rate of liquid nitrogen was 0.5 litres per min. Machining time for cryogenic is taken from Table 3 and calculated the cost of liquid nitrogen against each combination as given in Table 6.

Table 6 Cost of coolant for iso-response values of R_a

Combination	Coolant cost, PKR		
	Dry	Conventional	Cryogenic
1	0	19.625	1.8
2	0	7.85	1.8
3	0	53.575	1.8
4	0	14.95	1.8
Average	0	24	1.8

Cost of coolant found very less for cryogenic cooling as compared with the conventional machining for iso-response values of surface finish. It is about 13 times cheaper from conventional coolant on average basis.

3.3 Machining cost comparison

Using the values of electricity cost (C_e), overhead cost (C_{oh}), cutting tool cost (C_t) and wasted coolant cost (C_{cw}) in Eq. 2, the Machining cost was calculated for each scenario of dry, conventional and cryogenic cooling and shown in Table 7.

Table 7 Calculated machining cost

Combination	Machining cost, PKR		
	Dry	Conventional	Cryogenic
1	1014.18	1027	1007.19
2	1007.08	1010.8	1007.19
3	1014.18	1073.7	1007.19
4	1005.67	1020.56	1007.19
Average	1010.278	1033.015	1007.19

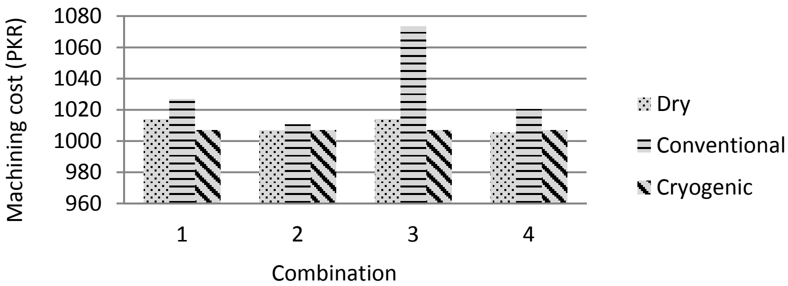

Fig. 5 Machining cost comparison

In calculated values of machining cost of Table 7, the effect of cutting tool cost (C_t) was for two inserts in each case. While machining time is increased, the cutting tools for dry machining will more rapidly wear as compared to conventional and cryogenic cooling. Therefore the cutting tools cost for dry machining will increase rapidly.

Machining cost comparison given in Fig. 5, shows that machining cost is less for cryogenic as compared with dry and conventional.

3.4 Tool wear analysis

Cutting inserts used in machining were analysed to check wear and damage using SEM. In dry machining the cutting tool nose tip was damaged by a length of 1250.68 μm and cutting edge by 1453.91 μm as shown in Fig. 6. Maximum flank wear of 338.82 μm was observed as shown in Fig. 7(a). Cutting tool using coolant was slightly damaged by 68.27 μm as shown in Fig. 7(b), whereas no tool wear was observed in cryogenic cooling as shown in Fig. 7(c).

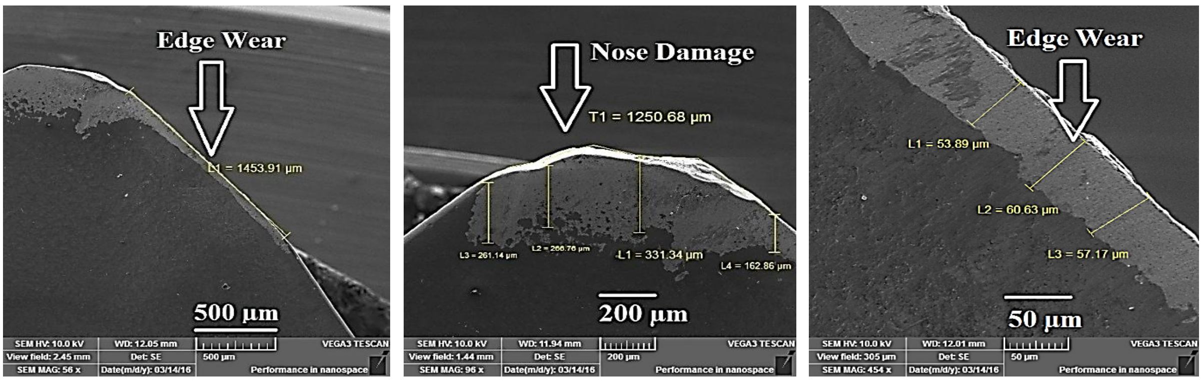

Fig. 6 Tool wear in dry cutting

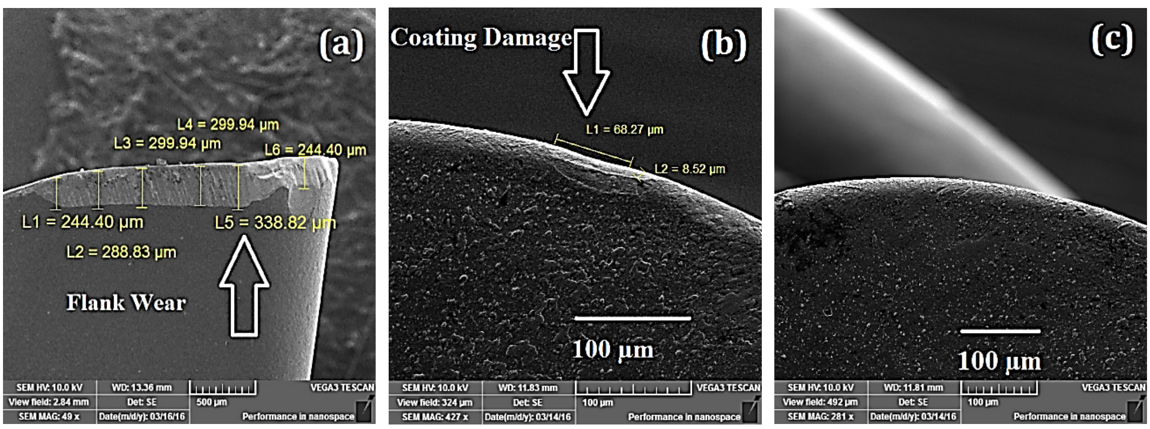

Fig. 7 Flank wear in dry cutting (a), Tool wear using coolant (b), Cutting tool wear using cryogenic cooling (c)

The cutting tools made of tungsten carbide used for experimentation have coating layer of (Ti, Al) N processed by technique of physical vapour deposition (PVD). This layer prolongs tool life when compared to cemented carbide under same cutting conditions. This coating layer was damaged in dry machining as shown in EDX analysis given in Fig. 8. The base tool material which is tungsten carbide found exposed by 60 %. Coating was damaged in tools used for dry machining only whereas no damage was observed for tools used in conventional and cryogenic machining.

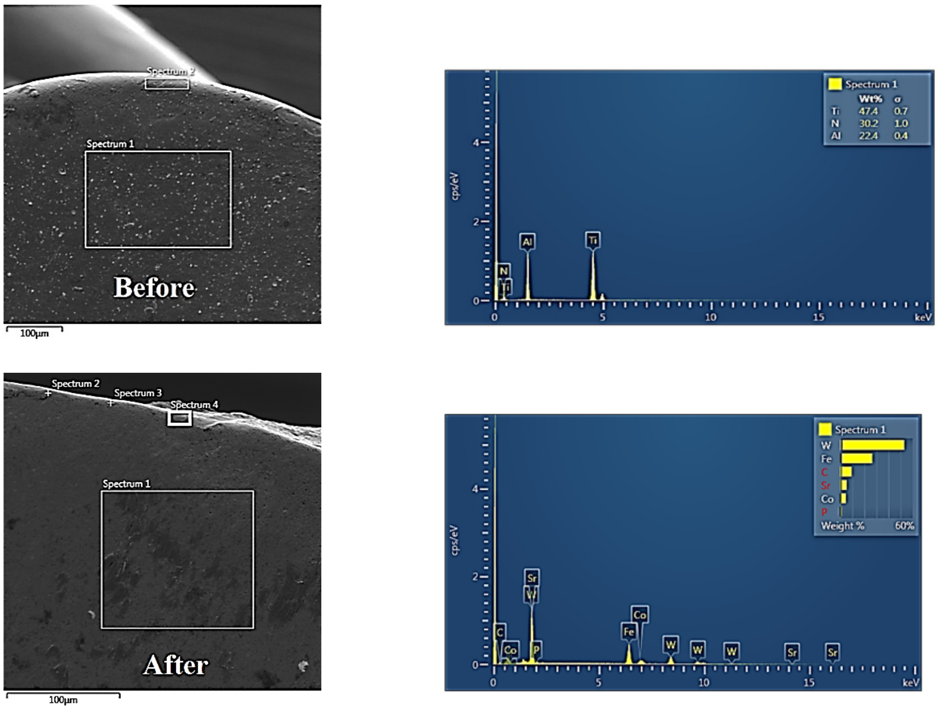

Fig. 8 EDX analysis of coating layer on cutting tool used in dry machining

4. Energy, waste, environmental, and social impacts

Cutting power and material removal rate are calculated for iso-response values of surface finish given in Table 3. Fig. 9 shows results obtained from the analysis and are related to sustainable machining:

Cutting Power: It was found that the cutting power required in cryogenic machining is 61.9 % less than cutting power required in dry machining.

Machining Cost: It is found that 47.55 % less electricity cost as compared with dry and 14.22 % less as compared with conventional machining.

Adverse effects of CLF: The adverse effects of conventional coolants are reduced by replacing the coolant with N_2 gas. Corresponding cutting power and machining cost are also reduced.

Machining time: Machining time for cryogenic is 15.12 % less than dry and conventional machining 12.51 % less than dry case.

Material Removal Rate: The material removal rate is 81.12 % more for cryogenic than dry machining.

Tool Life: Cutting tools life is 10.76 times more for cryogenic cooling which indicates that the waste in the form of damaged tools is reduced. On the other hand tool life is increased, productivity is enhanced by increasing the material removal rate and effective utilization of resources is ensured by reducing the machining times as shown in Fig. 9. Comparison of cutting power, cutting time, electricity cost, coolant cost, machine operating cost, material removal rate and tool life on average basis is presented in Table 8.

Table 8 Average response values calculated for nearly identical R_a

Sr.	Response	Units	Dry	Conventional	Cryo
1	Cutting power	KW	6.33	5.43	3.32
2	Cutting time	min	0.959	0.839	0.814
3	Electricity cost	PKR	6.33	5.43	3.32
4	Coolant cost	PKR	0	24	1.8
5	Machine operating cost	PKR	3.95	3.33	2.07
6	Material removal rate	mm^3/min	1.578	3.247	2.858
7	Tool life	min	99	318.6	1065

It is learnt that nitrogen gas is not harmful for the workers and environment, whereas the coolant used in the conventional machining had its adverse effects on the environment. This advocates use of cryogenic as more sustainable for machining and help workers life.

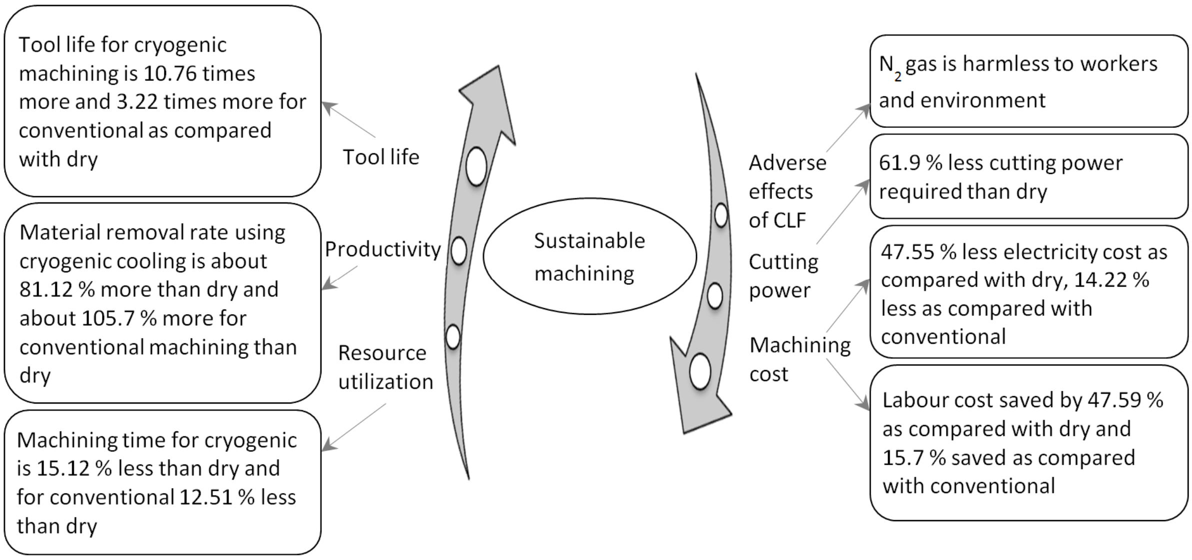

Fig. 9 Sustainable machining results using cryogenic cooling

5. Conclusion and future study

Findings of the experimental work using iso-response technique of evaluation are summarized as below:

- Tool life calculated for nearly identical response values of R_a and fond that maximum tool life for dry machining is 225 min, for conventional it is 643 min and for cryogenic it is 1065 min. On average Basis, the tool life for cryogenic machining is about 10.76 times more than that for dry and 3.22 time more for conventional than for dry. Also in overall comparison of dry & conventional it was found that tool life is maximum for cryogenic. Due to the increased tool life, the cost for the cutting tools is also reduced and productivity is increased. Waste in the form of worn tools is also reduced.
- Machining cost including the electricity consumption cost by machine and operating cost are based on time of machining operation; it is found that the time of machining is less in cryogenic cooling mode as compared with dry and conventional therefore overall cost is less for cryogenic cooling.
- Overall impact of machining cost including electricity cost, labour cost, cutter tools cost resulted that cryogenic machining is cheapest of all and hence sustainable. Nitrogen gas is harmless for workers and environment.

For future study, the technique of iso-response value can be applied for sustainability assessment of other difficult-to-machine materials. Process of machining other than face milling may be considered for evaluation. Cutting force may be introduced as response value and effect of different tool nose radii may also be investigated.

Acknowledgement

Authors would like to acknowledge the experimentation facility provided by the mechanical/industrial engineering department of UET, Taxila for the completion of research work.

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ISSN 1854-6250

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