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Original Article

Fuzzy logic based scheduling of the product families in reconfigurable manufacturing systems

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Abstract

Reconfigurable manufacturing system is the new type of manufacturing system which is designed for a part family and it can change its function and capacity by rearranging of software and hardware components whenever required**.** In a manufacturing system, products and/or product families are needed to be scheduled to get more productivity and profit**.** In the present work, fuzzy logic based model has been prepared for scheduling of the part families for reconfigurable manufacturing system considering the industrial case**.** For scheduling of products, three criteria have been considered; reconfiguration effort, profit over cost and due date**.** Fuzzy rules have been developed according to behavior of these criteria**.** Fuzzy logic model has been made in MATLAB**.** This model can be used to predict the schedule for maximum for considering reconfiguration effort and due date**.** Results of the model have been compared with weighted aggregate sum method**.**

Keywords: reconfigurable manufacturing system, reconfigurable machines, scheduling, fuzzy logic, fuzzy rules

1. Introduction

Reconfigurable manufacturing systems (RMSs), which possess the advantages of both dedicated serial lines and flexible manufacturing systems, were introduced in the mid-1990s to address the challenges initiated by globalization. The principal goal of an RMS is to enhance the responsiveness of manufacturing systems to unforeseen changes in product demand. RMSs are cost-effective because they boost productivity and increase the lifetime of the manufacturing system (Koren, Gu, & Guo, 2018). RMS is adjustable to the fluctuating demands and it can be easily upgraded with new process technology (Goyal, Jain, & Jain, 2013; Koren & Ulsoy, 1997; Prasad & Jayswal, 2017c, 2018). It has six key characteristics which are modularity, integrability, scalability, convertibility, customization, and diagnosability. The key characteristics customization, scalability, and convertibility are essential RMS characteristics, while the other three (modularity, integrability, and diagnosability) reduce the system configuration time and its ramp-up time (Koren, 2006; Prasad & Jayswal, 2017b, 2017c, 2019a, 2019b). RMS combines features of dedicated and flexible systems.

Reconfigurable manufacturing system has been evolved from dedicated manufacturing system. With the concept of using the modular machine, the concept of reconfiguration arises. But it is not limited to modular machines. Some researchers have given the concept of reconfiguration by material handling systems (Oke, Abou-El-Hossein, & Theron, 2011a), reconfiguration by relocation (Lee, 1997), and reconfiguration process plan (Youssef & ElMaraghy, 2006).

Koren and Shpitalni (2010) have given the concept of practical reconfigurable manufacturing system using cell gantry and spine gantry. It is like a special type of layout of flexible manufacturing system. Later reconfigurable machines were added (Koren, 2013). Authors have done the work on configuration selection (Ashraf, M., & Hasan, F., 2018), machine allocation (Ashraf, Hasan, & Murtaza, 2018), product family formation (Ashraf & Hasan, 2015). Reconfigurability has been reviewed in mining industry (Makinde, Mpofu, & Popoola, 2014), mold and die making industry (Oke, Abou-El-Hossein, & Theron, 2011b), Arvin Meritor industry (Abdi & Labib, 2003), and powertrain industry (Koren, 2013),

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Continental Automotive (Prasad & Jayswal, 2017a, 2017c, 2018b, 2019a).

Initially, when the demand of products was low, process type systems were used. But when the demand of certain products increased, separate cells were designed for those products. Initially, cells were designed for single product but as the variety of the products increased, industries started to design the product for a group. Researchers were focusing for the group the products so that a manufacturing cell should be designed but after the development of the concept of reconfiguration even that part family is grouped in the small groups/families so that cell can easily be reconfigured between one subgroup to another subgroup (Prasad & Jayswal, 2019a).

Scheduling is one of the most important steps in production control. Scheduling may be defined as "*fitting specific job into a general time-table so that orders may be manufactured in accordance with contracted liability or in mass production so that each component may arrive and enter to assembly in order and at the time it is required. In other words, scheduling is that phase of production control which rates the work in order of its priority and provide for its release to the plant at the proper time and in the correct sequence*." Thus, scheduling is concerned with when work shall be performed on a product or part. Scheduling in manufacturing system can be done on the basis of some rules such as, FCFS (first come first serve), LCFS (last come first serve), SPT (shortest processing time), LPT (longest processing time), EDT earliest due date, maximum profit over cost, reconfiguration cost/reconfiguration effort, random (on the choice of manager). scheduling can be done for one criterion as mentioned above or more than one criterion (Prasad & Jayswal, 2018c).

The fuzzy set theory has been proposed in 1965 by Zadeh. This theory is based on the intuitive reasoning by taking into account the human subjectivity and imprecision. It is not an imprecise theory but a rigorous mathematical theory which deals with subjectivity and/or uncertainty which are common in the natural language (Klir & Yuan, 1996; Werro, 2015). A crisp set is defined by a bivalent truth function which only accepts the values 0 and 1 meaning that an element fully belongs to a set or does not at all, whereas a fuzzy set is determined by a membership function which accepts all the intermediate values between 0 and 1. Values of a membership function, called membership degrees or grades of membership, precisely specify to what extent an element belongs to a fuzzy set, i.e. to the concept it represents. A fuzzy set A on X is a mapping $A : X \rightarrow [0,1]$. An equivalent definition is given by $A = (x, \mu_A(x)) \mid x \in X$ with $\mu_A : X \rightarrow [0, 1]$, explicitly providing the membership degree of each $x \in X$. This definition attempts to identify the FS (Fuzzy set) with the graph of the mapping A. Many other notations have been used for fuzzy sets in the literature (Bustince *et al.*, 2016).

The fuzzy logic theory is based on fuzzy sets and it deals with the last kind of ambiguity, the fuzziness. It proposes mathematical notions to model the imprecision of the human thinking. Considering that the fuzziness is ubiquitous and essential for the human beings, the fuzzy logic theory offers new perspectives for improving the human-machine interactions. One important aspect of this approach is the ability of processing intuitive and human-oriented queries based on linguistic terms or expressions (Werro, 2015).

Fuzzy logic has been used in many applications such as adaptive food recommendations (Osman *et al.*, 2017), for predicting surface roughing (Barzani *et al.*, 2015), sobel edge detection method (Gonzalez, Melin, Castro, Mendoza, & Castillo, 2016), wind turbine systems (Van, Nguyen, & Lee, 2015), medical expert systems (Korenevskiy, 2015) etc.

Scheduling problems in reconfigurable manufacturing system have been solved by MCDM (Prasad & Jayswal, 2017c, 2018). Main limitation of these MCDM techniques is that priority with the criterion either increases or decreases but actual relations are not so simple. These relations can be described in a better way by using fuzzy base rule. The literature shows that fuzzy logic provides good results in decision making. Therefore, a fuzzy rule base system has been developed considering the industrial application.

2. Fuzzy Logic Model

In this paper, mamdani system has been used as graphical technique of interference (controller). Here some rules are given in terms of if, then. It has been prepared using fuzzy logic tool box in Matlab. It consists of a fuzzy logic designer, membership function editor, rule editor, rule viewer, and surface viewer (Figure 1): *FIS Editor*: It displays the information about fuzzy system. *Membership Function Editor*: Input and output variables are added and edited by using it. *Rule Editor*: Fuzzy rules are added in the system. *Rule Viewer:* It helps to study the effect of changing input variables. *Surface Viewer*: It generates a 3-D surface from two input variables and the output. In fuzzy logic system centroid Method has been used for defuzzification.

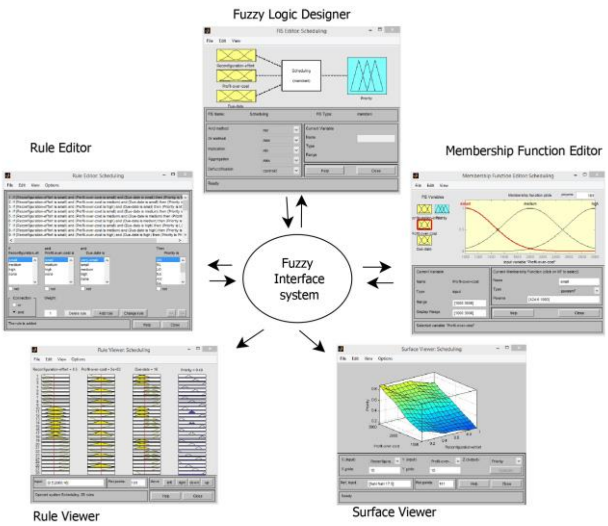

Figure 1. Fuzzy interface system

2.1 Criteria considered

In present paper, three criteria have been considered based on the case study (Prasad & Jayswal, 2017c). These are; reconfiguration effort, profit over cost, and due date. These are discussed as below;

2.1.1 Reconfiguration effort

It is the effort for changing its configuration from one type of product family to another type of product family.

Reconfiguration effort can be at three levels, market level reconfiguration effort, system level reconfiguration effort, and machine level reconfiguration effort.

The market level reconfiguration effort (*MKRE*) is associated with the activities that are performed outside the boundaries of the manufacturing system such as financial activities, shipping activities, bidding activities, logistic activities etc., that are associated with purchasing new machines or machine modules, selling old machines or modules and renting machines or modules. System level reconfiguration effort (*SRE*) is associated with the activities that are performed within the boundaries of the manufacturing system but at a level higher than machines. These activities include adding, removing or adjusting the machines in the system, relocating the machines and changing the material flow path. Machine level reconfiguration effort (*MRE*) is associated with the activities that are performed inside the boundaries of the manufacturing system and are all within the limits at the machine level. These activities include the adding, removing or adjusting machine modules and adding, removing or adjusting operation clusters. For all the activities reconfiguration effort is calculated separately by considering machines and/or modules added, removed or adjusted. Total reconfiguration effort (*TRE*) can be calculated as the weighted sum of the all three level reconfiguration efforts, Equation 1.

$$TRE = \psi_1 MKRE + \psi_2 SRE + \psi_3 MRE \quad (1)$$

where ψ_1, ψ_2, ψ_3 are weights assigned to the all three types of reconfiguration effort. $\psi_1 + \psi_2 + \psi_3 = 1$

In the present case, only two types activities have been considered, (i) addition/removal of machines (system level) and (ii) addition and removal of modules (machine level) System level reconfiguration effort can be calculated as

$$SRE_{group-1/2/3} = \alpha \frac{No.of\ machines\ added}{Total\ no\ of\ machines} + \beta \frac{No.of\ machines\ removed}{Total\ no\ of\ machines} + \gamma \frac{No.of\ machines\ removed}{Total\ no\ of\ machines} \quad (2)$$

α, β, γ are the weights assigned to addition, removal and adjustment respectively. $\alpha > \beta > \gamma$ and $\alpha + \beta + \gamma = 1$.

$$SRE = \zeta_1 SRE_{group-1} + \zeta_2 SRE_{group-2} + \zeta_3 SRE_{group-3} \quad (3)$$

where $\zeta_1, \zeta_2, \zeta_3$ are weights assigned to the all three types of reconfiguration effort.

Machine level reconfiguration effort can be calculated as General formula for reconfiguration effort can be written as,

$$MRE = \alpha' \frac{No.of\ modules\ added}{Total\ no\ of\ modules} + \beta' \frac{No.of\ modules\ removed}{Total\ no\ of\ modules} + \gamma' \frac{No.of\ modules\ removed}{Total\ no\ of\ modules} \quad (4)$$

where α', β', γ' are the weights assigned to addition, removal and adjustment respectively. $\alpha' > \beta' > \gamma'$ and $\alpha' + \beta' + \gamma' = 1$.

If in a manufacturing system, there are *n* modular machines which are needed to be reconfigured for another type of product; total number of modules added, removed or readjusted can be calculated by using following formulas.

$$No.of\ module\ added = \sum_{i=1}^{n} (N_i \times modules\ added\ in\ M_i)$$

$$No.of\ module\ removed = \sum_{i=1}^{n} (N_i \times modules\ removed\ in\ M_i)$$

$$No.of\ module\ readjusted = \sum_{i=1}^{n} (N_i \times modules\ readjusted\ in\ M_i)$$

$$Total\ no\ of\ modules = \sum_{i=1}^{n} (N_i \times modules\ in\ M_i)$$

$$Total\ no\ of\ modules = Total\ no\ of\ modules\ added + Total\ no\ of\ modules\ removed + Total\ no\ of\ modules\ readjusted$$

where N_i = number of machine required for i^{th} operation; M_i= machine required for i^{th} operation

2.1.2 Profit over cost

Profits are the difference between revenues and costs. Profit over cost can be calculated by multiplying the number of products produced i.e. demand of the product to the profit per product. Profit over cost depends on the demand of the product and demand is an important factor in a manufacturing system. Higher profit is the goal of an industry, hence it has been considered as a criterion for scheduling.

2.1.3 Due date

Another criterion which has been considered is due date. If due date is close i.e. there are fewer days left for delivery, then its priority should be high.

2.2 Membership functions

Reconfiguration effort has been assigned with triangular membership functions and divided into three zones small, medium and high. Profit over cost has been assigned with Gaussian membership function and divided into three zones small, medium and high. Due date has been assigned with trapezoidal membership functions and divided into four zones very small, small, medium and high. The output of these variables is priority varying from 0 to 1. The priority variable is assigned with triangular membership function and divided into nine parts; minimum (MN), negative low (NL), low (LO), negative average (NA), average (AV), positive average (PA), high (HI), positive high (PH) and maximum (MX); Figure 2.

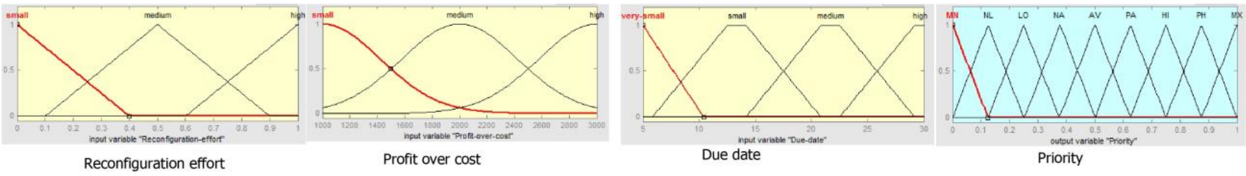

Figure 2. Membership functions

2.3 Rules

Rules have been shown in Table 1. Twenty-eight rules have been given in the model. For example, if reconfiguration effort is small and profit over cost is small and due date is small then priority is negative average (NA). Reconfiguration effort is small and profit over cost is medium and due date is small then priority is positive average (PA).

Table 1. Fuzzy rules

RE	Profit over cost			Due date
	small	medium	high	
small	NA	PA	MX	small
small	LO	PA	MX	medium
small	LO	AV	PH	High
medium	LO	AV	PH	small
medium	NL	AV	PH	medium
medium	NL	AV	PH	High
high	NL	AV	HI	small
high	MN	NA	HI	medium
high	MN	NA	PA	medium
		MX		very high

3. Problem Formulation

Problem used in the illustrative example is inspired by the research work done by the author in Continental Automotive Components (India) Pvt. Ltd and given in (Prasad & Jayswal, 2017c). In this problem, there are seven machines. Machines have been grouped as group 1, group 2 and group 3 as shown in Table 2. Machine M2 and M4 are modular machines which can change their configurations. Configurations of machine M2 are M_2^1 and M_2^2 . Configurations of machine *M*4 are M_4^1 and M_4^2. Auxiliary modules are {1, 2, 3, 4, 5, 6, 7, 8, 9, 10}. Four types of product families are manufactured named as product family A, B, C and D. $\psi_1 = 0$, $\psi_2 = 0.7$, $\psi_1 = 0.3$, $\zeta_1 = 0.6$, $\zeta_2 = 0.3$, $\zeta_3 = 0.1$, $\alpha = 0.5$, $\beta = 0.4$, $\gamma = 0.1$, $\alpha' = 0.5$, $\beta' = 0.4$, $\gamma' = 0.1$.

If initially product family A is running in manufacturing system, then system can be reconfigured for part family B, part family C, and part family D. Reconfiguration effort for changing the configuration from A to B,

Group-1 machine added = {M1} = 1
Group-1 machine removed = {} = 0
Group-1 machine adjusted = {M2, M4} = 2

$$SRE_{group-1} = 0.5 \times \frac{1}{3} + 0.4 \times \frac{0}{3} + 0.1 \times \frac{2}{3} = 0.2333$$

Similarly, $SREgroup{-}2 = 0.4$, $SREgroup{-}3 = 0.45$

$$SRE_{A-B} = 0.6 \times 0.2333 + 0.3 \times 0.4 + 0.1 \times 0.45 = 0.305$$

modules added = {1,4,7} = 4
modules removed = {2,5,9} = 3
modules readjusted = {3,6,8} = 3

$$MRE_{A-B} = 0.5 \times \frac{4}{10} + 0.4 \times \frac{3}{10} + \times \frac{3}{10} = 0.35$$

$$TRE_{A-B} = 0.7 \times 0.305 + 0.3 \times 0.35 = 0.3185$$

Similarly, $TRE_{A-C} = 0.114$, $TRE_{A-D} = 0.3255$

Reconfiguration effort, profit over cost, and due date have been shown in Table 3. It shows the calculated values of total reconfiguration effort. For profit over cost and due date, values are considered. These are most likely happed values.

Table 2. Machine configurations for part families A, B, C, and D

Group	Machines	Machine configurations	Auxiliary modules	A	B	C	D
Group -1	M1				✓		✓
Group -1	M2	M_2^1	{1,3,4,6,7}		✓		✓
		M_2^2	{2,3,6}	✓		✓	
Group -2	M3			✓		✓	
Group -1	M4	M_4^1	{5,8,9}	✓		✓	
		M_4^2	{8,10}		✓		✓
Group -3	M5				✓	✓	
Group -2	M6						✓
Group -1	M7			✓			

Table 3. Total reconfiguration effort, profit over cost and due date of product families B, C and D

Initially PRODUCT A			
After reconfiguration	TRE	Profit over cost ($\times 10^3$ INR)	Due date
Product family B	0.3185	2700	12
Product family C	0.1140	2000	10
Product family D	0.3255	2300	17

4. Results and Discussion

Priority of the schedule has been calculated by the fuzzy model shown in Figure 1. Relationship of input variable to output variable has been shown in Figure 3. It shows that when reconfiguration cost is increasing, priority is decreasing. When profit over cost is increasing, priority is increasing. When due date is very small, priority is high, after that it has not much

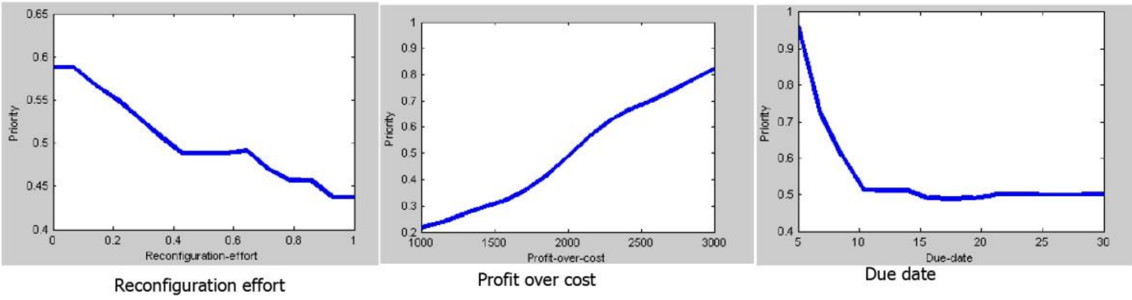

Figure 3. Relationship between input output variables

effect on priority. Figure 3 shows that rule used in fuzzy model shown in Table 1 are correct.

Priority of the part families for the most likely values shown in Table 3 has been calculated and shown in Table 4. It shows that priority of product family B is highest; therefore its ranking is Ist. Therefore, schedule will be, product families *B* → *D* → *C*. If product families are scheduled only for shortest reconfiguration effort rule, then schedule will be *C* → *B* → *D*. If product families are scheduled only for highest profit over cost, then schedule will be *B* → *D* → *C*. If product families are scheduled only for shortest due date rule, then schedule will be *C* → *B* → *D*, Table 3. But if part families are scheduled for combined effect of reconfiguration effort, profit, and due date then schedule is *B* → *D* → *C*, Table 4.

4.1 Comparison of result with weighed aggregate sum method

Results of fuzzy logic model are compared with the results of weighted aggregate sum (WAS) method. In WAS (Zavadskas, Turskis, Antucheviciene, & Zakarevicius, 2012), values are normalized as shown below. If max value is desirable, normalized value ($x*_{ij}$) for value (x_{ij}) is calculated as

$$x_{ij}^* = \frac{x_{ij}}{max(x_{ij})}.$$

If min value is desirable, normalized value ($x*_{ij}$) for value (x_{ij}) is calculated as

$$x_{ij}^* = \frac{min(x_{ij})}{x_{ij}}.$$

In the problem, normalized values have been calculated and shown in Table 5. Weighted sum has been calculated when equal weights have been given to each criterion (0.3333, 0.3333, 0.3333). It shows that the schedule will be *C* → *B* → *D*. If the weights are changed to 0.1, 0.85, 0.05, schedule becomes *B* → *D* → *C*, Table 5.

Two major observations can be concluded while comparing the fuzzy model and WAS;

1) In fuzzy, priority is high when due date is very small, Figure 3. In WAS, it cannot be broken into segments. Weight is assigned to due date, it can be anything between 0 to 1.
2) In fuzzy range is defined for possible minimum values to possible maximum valves. But in WAS range is only for the given data sets. For example, range of reconfiguration effort can be from 0 to 1. Therefore, it has been provided in fuzzy system but in WAS, it will be from 0.1140 to 0.3185.
3) One more problem occurs in MCDM that is rank reversal, i.e. if any new alternative is added to the system, sometimes rank is changed. This problem also can be resolved using fuzzy system.

Table 4. Ranking

	Priority	Ranking (fuzzy logic)
Product family B	0.7360	1
Product family C	0.6110	3
Product family D	0.6370	2

Table 5. Ranking using weighted sum method.

	Normalized values			Weighted sum	Ranking
	TRE	Profit over cost	Due date		
Product family B	0.3579	1	0.8333	0.7303	2
Product family C	1	0.7407	1	0.9135	1
Product family D	0.3502	0.8519	0.5882	0.5967	3

5. Conclusions

In this paper, fuzzy logic rule based model has been prepared for scheduling of product families in reconfigurable manufacturing system. The problem is inspired by the industrial case study. The salient points of the research are as following;

1) The criterion considered for scheduling are reconfiguration effort, profit over cost, and due date. The methodology for calculation of reconfiguration effort has been discussed.
2) Membership functions of reconfiguration effort, profit over cost, and due date are triangular, Gaussian, and trapezoidal respectively. The output variable, priority has triangular function, Figure 2.
3) Rules of the model have been shown in Table 1. Relations between input and output variables have been shown in Figure 3. It shows that when reconfiguration cost is increasing, priority is decreasing. When profit over cost is increasing, priority is increasing. When due date is very small,

priority is high, after that it has not much effect on priority.

Result of fuzzy model has been compared with the results of WAS method. It differs in three ways (i) due date has been given high priority when it is very less otherwise its priority is minimum. Thus, it provides important for the particular segment (ii) it can be defined for possible range (iii) priority does not change with addition of any new alternative.

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