Investigating barriers due to difficult interfaces as driver for other barriers in Reconfigurable Manufacturing System

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***Abstract*— As we progress towards an economy in which the movement of objects, both large and small, is swift, meeting the demand & supply of these becomes of ultimate importance to the organizations. To fulfil this, we are witnessing a shift from traditional manufacturing system to a reconfigurable manufacturing system, where changing the configuration of the system produces a different output altogether. It comes with various risks as well. For instance, the change in configuration might make the interface more complex to operate. Or maybe, the different varieties of outputs from the same system require different handling which may be difficult. The purpose of this paper is to empirically test a structural model based upon three important risk factors, i.e.: 1) barrier due to difficult interface; 2) barrier due to expensive tooling; 3) barrier due to difficulty in variety handling. Various statistical techniques were used to verify, validate and test the reliability of the hypothesis and their sub dimensions. Results of structural equation modelling revealed that difficult interface has a positive and significant effect on expensive tooling(0.76) and expensive tooling has a positive and significant effect on difficulty in variety handling(0.7).**

Keywords— reconfigurable manufacturing system; barriers; difficult interface; DI; expensive tooling; ET; difficult variety handling; DVH; structural equation modelling; SEM.

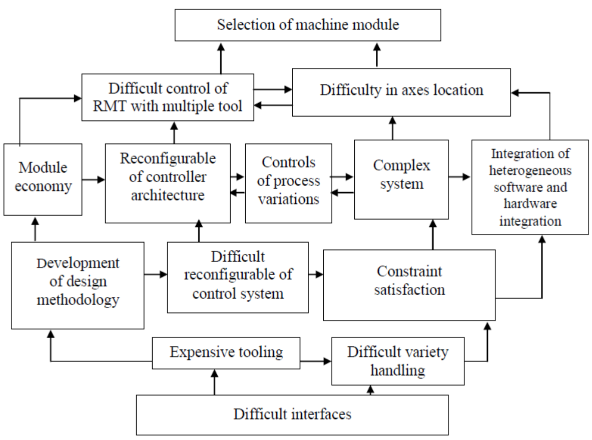
I. Introduction

In today's global marketplace, customer needs are becoming increasingly dissimilar and the need for customization and new products features is intensifying [1]. Recently, a study indicated that product variety has more than doubled in the period from 1996 to 2012, and that the duration of product life cycles at the same time has decreased on average 30 percent. Moreover, there is evidence that the time for new products to be absorbed in the market has decreased significantly[2]. In this respect, time-to-market and quick production ramp-up is becoming increasingly critical to the success of manufacturing companies, which means that the requirements imposed on the manufacturing systems have changed [3]. In the past, manufacturing systems were developed for one ramp-up period with subsequent long and stable periods of producing only a few variants [4]. Currently, the frequency of new products is increased and time for designing, building, and ramping-up volumes has been reduced, which means that the manufacturing systems must be built for rapid change in accordance with the market [5]. For that reason, the reconfigurable manufacturing system (RMS), which can be repeatedly changed in capacity and functionality in a cost efficient way, has been widely labelled the manufacturing system of the future[6].

In the manufacturing industry, some of the challenges faced by manufacturers include reducing the lead time, increasing the quality, and providing a variety of products. Although dedicated manufacturing lines (DMLs) the traditional manufacturing system are capable of producing the similar products in bulk but are incapable of accommodating the product variety. On the other hand, Flexible manufacturing systems (RMSs) are capable of accommodating the product variety but in comparison to DML the productivity is low [6]. Besides that the cost of RMSs are very high and therefore have very limited acceptability among the manufacturers [7]. Reconfigurable manufacturing systems (RMS) a new type of manufacturing system has the capability to adjust both capacity and functionality in order to cope up with product variety and production volume[8]. The overall vision of reconfigurable manufacturing systems (RMSs), as systems of equipment, having a modular structure, that have customised flexibility so one can easily reconfigure the entire system to produce a family of products at different production volumes. A reconfigurable manufacturing system (RMS) is one designed at the outset for rapid change in its structure, as well as its hardware and software components, in order to quickly adjust its production capacity and functionality within a part family in response to sudden market changes or intrinsic system change.

Clearly reconfigurable manufacturing meets challenges in today's global manufacturing environment that traditional approaches to manufacturing are not able to [9]. In particular, the RMS concept offers a solution to the challenge of rapidly and efficiently ramping-up volumes and varieties, as its modular structure allows for reduced time for designing, building, and redesigning the system. Thus, systematic and continuous design and ramp-up are cornerstones of the RMS concept and will occur numerous times in its lifetime. However, developing manufacturing systems that are able to be reconfigured poses various challenges compared to dedicated manufacturing. Currently, various different design frameworks and methodologies exist, but their industrial application has not yet been proven [10]. Owing to the complex nature of the reconfigurable manufacturing system because of its interface between machines, organisations, processes, technologies and tacit knowledge of employees, it is very difficult to analyse the inter-relationship among the various barriers. Therefore, the aim of this paper is to investigate barriers due to difficult interfaces as a driver for other barriers in reconfigurable manufacturing systems towards their adoption in industry.

With the help of interpretive structural modelling (ISM) approach, Malhotra et al. (2014) developed an interrelationship model of barriers to reconfigurable manufacturing systems as shown in Figure 1. According to Malhotra et al. (2014), difficult interfaces, barriers due to expensive tooling, difficult variety handling, etc., are independent barriers, i.e., they are not affected by any means and have great influencing power, thus if these barriers are mitigated, then other barriers show less impact. In this modelling, only influences are derived but quantitative information of influence is not mentioned due to the limitations in the ISM model. Structural equation modelling (SEM) has properties of confirmatory factor analysis (CFA) and structure modelling. The limitation of SEM is that it may not develop an initial model and this shortcoming might be overcome by using the model given in Figure 1.



Based on the above discussion, the objective of this paper is:

• *To identify the dimensions of barriers due to difficult interfaces(DI) that significantly influences the expensive tooling(ET) and difficult variety handling(DVH).*

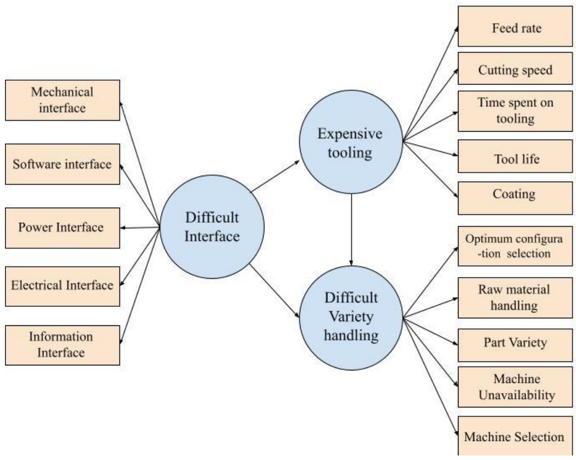
Based upon the review of literature on DI, barriers due to ET and DVH, authors intend to empirically examine the interrelationship of all three barrier parameters. To this effect, authors proposed a framework based on Figure 1 with few boundary conditions. After proposing the framework, constructs were developed and tested empirically using data collected through a survey questionnaire. Further, SEM was used to test the hypothesised relationship between all three barrier parameters. The remainder of this paper is organised as follows. Section 1 consists of introduction and Section 2 provides a literature review and proposed model based on ISM approach [11]. Section 3 describes research methodology including the construction of measures and instruments, the survey procedure, scale reliability, exploratory factor analysis (EFA), CFA, result of SEM and findings related to hypothesis. Conclusions of the study are presented in Section 4.

II. CONCEPTUAL MODEL AND LITERATURE REVIEW

A. *Conceptual model*

Figure 2 presents the conceptual framework, which is used in this work as a research framework based on Figure 1, with few boundary conditions with respect to the ISM model [11].

Figure 2 Research framework



The research framework as shown in Figure 2 depicts that DI factor has an impact on ET factor directly, also on DVH factor and ET has an impact on difficult variety handling.

B. *Literature Review*

i) Difficult Interface

a) Barriers due to mechanical interface

Designing a system with a combination of modules from different manufacturers requires standardisation of the mechanical interfaces [12]. In such cases, the mechanical interfaces that are specified by geometric features, have associated tolerances. The undesirable addition and/or superposition of tolerance fields can have a negative effect on the machine accuracy after reconfiguration [13]. For example, connectors, fasteners, bolts.

b) Barriers due to software interface

The heterogeneous software and hardware components that are developed by different vendors at different times. This will require special software and electrical interfaces. So integration of heterogeneous software is a big problem [11]. To guarantee easy reconfigurability, not only the physical system must be updated, but also the management and control software must take into account the new characteristics of the plant [13].

c) Power Interface

The three types of interfaces used in RMS for machine modules include information interface, power interface and mechanical interface. Power interfaces include electricity, hydraulics, pneumatics [14].

d) Electrical Interface

Higher up, the continuous real-time control layer typically has electrical interfaces such as time-varying voltage signals. In level 2, the discrete execution control interfaces are simultaneously electrical signals and binary information [15].

e) Information Interface

Detailed information concerning the product, such as the process plan, demand, etc., can be incorporated in the model to evaluate the cost and time required to make the conversion or changeover from the current state to the required state [16]

ii) Expensive tooling

• In the last few decades, supply chain management has emerged as an important strategy and practice, which can help organizations in aligning their functions efficiently [17].
• The reconfigurable machine requires expensive tooling. Sometimes the tools from two to six sets of which are generally required may cost as much as machines.

The sub factors of expensive tooling are:

a) Feed rate

The thickness of each layer can be varied by adjusting the powder feed rate. Therefore, integrated hybrid systems are more adaptive than layer–based hybrid systems. In addition, MR processes are not performed for each layer, thereby improving system efficiency [18].

b) Cutting speed

Increasing processing speed with reduced feed and depth leads to a reduced cutting force, which is suitable in machining thin-walled objects. At high cutting speeds, the majority of heat is transferred in the separated particles, while the machining object and tool remain relatively cool [19].

c) Time spent on tooling

All supervisors determine the percentage of time spent on tooling, it could be hence decided that 'new design' from the engineering department was the single most important cause of tooling [20].

d) Tool life

The performance of these processes is still especially challenging because of unpredictable tool life of micro end mills, high wear rates and the negative impact of tool wear on dimensional accuracy and surface quality [21].

e) Coating

The coating should be able to yield maximum protection at the critical contact point between the tool and work piece in order to enhance the wear resistance capability [22].

iii) Difficult variety handling

• Implementation of RMS is a big problem because the large number of individualised products in RMS leads to a high variety of material items such as raw material, work in process [23].

The sub factors of expensive tooling are:

a) Optimum configuration selection

The selection of RMS configurations that include arrangement of machines, equipment selection, and assignment of operations, has a significant impact on their performance [24].

b) Raw material handling

The large number of individualised products in RMS inevitably leads to a high variety of material items such as raw material. So, it is essential to capture the high variety of material and end product in small models [25].

c) Part Variety

The component variety at Harnischfeger is in hundred thousands of parts, and poses a problem for the traditional methods of gathering data for machine-part matrices. The development of a procedure for dealing with this problem has been a part of this work as well as a step-by-step refinement of the final block-diagonal machine- part matrix for adaptation to the specific requirements of the manufacturing system at Harnischfeger. [26].

d) Machine Selection

The design and modelling of RMS, as well as the generation of process plans, are the most active research topics in this field. In this paper, our main focus is on the machine selection problem in RMS and their impacts on the [27].

e) Machine Unavailability

It represents the process plan perturbations that could be caused by unpredictable machine unavailability (failure, maintenance, reconfirmation errors[27].

C. Research hypothesis

The research framework proposed in the study clearly indicates that a difficult interface has a positive correlation with difficulty in variety handling and expensive tooling.

H1 Difficult interface has a positive and significant effect on the difficulty in variety handling.

The manufacturing process selection system interfaces on the data modelling aspect of the problem by presenting the data in a suitable format. So, it is essential to capture the high variety of material and end products in small models [28]. The different interfaces of different machines that are used in the production of a variety of materials present a difficulty towards the production of products of higher variety and diversity.

H2 Difficult interface has a positive and significant effect on expensive tooling.

It is difficult to modularly assemble the machines accurately enough to meet the accuracy requirement of machine tools. But the reconfigurable machine requires expensive tooling [28].

H3 Expensive tooling has a positive and significant effect on difficulty in variety handling.

Implementation of RMS is a big problem because a large number of individualised products in RMS leads to a high variety of material items such as raw material, expensive tooling in the process [23]. Since different products require some different types of tools to work on them, handling a variety of products will lead to spending an excess amount on the tooling inventory.

H0 The overall hypothesis model has a good fit.

III. RESEARCH METHODOLOGY

A. Survey Design

To examine the degree of structural relationship among DI, ET and DVH, a SEM is developed and three hypotheses related to difficult interface, expensive tooling, and difficult variety handling have been formulated. To test various research hypotheses a survey instrument was developed. The items and questions in the questionnaire were framed after critical review of the latest literature. The DI metrics consisted of five items [11;12;13;14;15;16]Similar to DI, the measures of ET indicators were derived and adopted from previous empirical studies [18;19;20;21;22] with five metrics. On the other hand dependent variables, i.e., DVH metrics were also derived from previous empirical studies [24;25;26;27]. After a few iterative reconsiderations and consecutive improvements in the questionnaire, the final questionnaire has been designed. On the basis of feedback received during the pilot test, the statements of the questionnaire were modified and a final questionnaire has been prepared for the survey.

The questionnaire related to the above mentioned hypothesis was developed using a five-point Likert scale ranging from 1 ‘strongly disagree’ to 5 ‘strongly agree’. In order to ensure the validity of the survey related to the study, Cronbach's α coefficient was calculated. The data and scale was reliable as Cronbach’s $\alpha > 0.70$ and is acceptable in literature [29].The respondents were from various organisations related to reconfigurable manufacturing systems situated in the northern part of India or near Delhi/NCR. The respondents were asked to indicate the level of influence of the factors affecting the DVH. Data was collected using self-administered questionnaires through personal contacts only. A total of 30 questionnaires were administered and completely filled.

B. EFA and scale reliability

The main applications of factor analysis techniques are:S

a) to reduce the number of dimensions

b) to detect structure in the relationships between factors.

Therefore, factor analysis is applied as a data reduction or structure detection method. In the present paper, EFA is used as reconfirmation of the existing model formation. Descriptive statistics and EFA along with the reliability of the dimensions related to factors of DI, DVH, and ET are presented in Table 1. With the help of SPSS-26, a factor analysis was performed on the response to the questionnaire. A principal axis factoring was performed using varimax factor rotation to verify the group of factors. Factor loadings linked to each of the three constructs shown in Table 1 are practically high. Further, Cronbach’s α coefficient analysis is used to find out the reliability of the data collected and their scale. Each of the factors has Cronbach's alpha > 0.70, thus, showing that the constructs are reliable.

TABLE 1 *DESCRIPTIVE STATISTICS AND RELIABILITY OF DIMENSIONS*

Exploratory factor analysis						
S. no.	***Barriers***	***N***	***Mean***	***Std. Deviation***	***Factor loading***	***Reliability***
	Difficult interfaces					
1	Mechanical interface	30	3.9	1.062	0.616	0.788
2	Software interface	30	3.97	1.033	0.613	
3	Power interface	30	3.9	1.155	0.621	
4	Electrical interface	30	3.93	1.015	0.747	
5	Informational interface	30	3.97	1.098	0.549	
	Expensive tooling					
1	Feed rate of tooling	30	3.83	0.95	0.791	0.793
2	Cutting speed	30	3.93	0.98	0.851	
3	Time spent on tooling	30	4	0.91	0.642	
4	Tool Life	30	3.93	1.112	0.631	
5	Coating	29	4.07	1.163	0.553	
	Difficulty in variety handling					
1	Optimum Configuration Selection	30	3.83	0.986	0.806	0.659
2	Raw Material Handling	30	4.03	1.033	0.638	
3	Part Variety	30	3.83	0.95	0.602	
4	Machine Selection	30	4.1	1.029	0.565	
5	Machine Unavailability	30	4.13	1.042	0.537	

C. Correlation analysis.

Pearson correlation analysis was conducted to examine relationship among the variables of DI, ET and DVH with themselves (Table 2). Table 2 shows significant and relationship (0.559) among informational interface and mechanical interface, and also between software interface and mechanical interface in RDPE. On the other hand in ET, cutting speed (0.580) has significant association with feed rate of tooling. Similarly, time spent on tooling (0.541) has the second highest correlation with cutting speed. Among DVH, machine selection has the maximum correlation with part variety (0.922).

TABLE 2 *PEARSON'S CORRELATION BETWEEN BARRIERS*

	Correlations					
	Dimensions	**1**	**2**	**3**	**4**	**5**
i)	Difficult Interface					
1	Mechanical interface	1.000				
2	Software interface	.531**	1.000			
3	Power interface	.498**	.430*	1.000		
4	Electrical interface	.410*	.524**	.406*	1.000	
5	Informational interface	.559**	0.272	.432*	0.215	1.000
ii)	Expensive Tooling					
1	Feed rate of tooling	1.000				
2	Cutting speed	.580**	1.000			
3	Time spent on tooling	.399*	.541**	1.000		
4	Tool Life	.446*	.439*	.443*	1.000	
5	Coating	.392*	.503**	.464*	0.221	1.000
iii)	Difficult Variety Handling					
1	Optimum Configuration Selection	1.000				
2	Raw Material Handling	0.040	1.000			
3	Part Variety	0.043	0.357	1.000		
4	Machine Selection	-0.119	.483**	.723**	1.000	
5	Machine Unavailability	0.157	0.284	.581**	0.245	1.000

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

TABLE 3 EXPLORATORY AND CFA

	EFA			CFA		
Barrier	*KMO*	*Eigen values*	*Percentage of variance explained*	*CFI*	*GFI*	*RMSR*
Difficult interface	0.766	2.725	54.503	0.914	0.901	0.025
Expensive tooling	0.791	2.802	54.047	0.931	0.912	0.022
Difficulty in variety handling	0.517	2.369	47.371	1	0.989	0.015

D. *Confirmatory factor analysis*

In order to establish the validity of the factors, CFA was carried out using IBM AMOS 26. Table 3 depicts both the exploratory factor and CFA for the three constructs. The goodness of fit index (GFI), comparative fit index (CFI), is higher than the level of 0.9, which indicates uni-dimensionality in the factors. The root mean square residual (RMSR) is below 0.05 and therefore it can be established that these conditions meet the requirement of a fit model.

E. *SEM results*

The theoretical framework demonstrated in Figure 2 has three hypothesized relationships between the factors related to DI, ET and DVH. Goodness fit test for SEM is performed to establish whether the particular variable provides an acceptable fit or not. The path diagram is shown in Figure 3 resulting from the SEM analysis using IBM AMOS 26. The model was evaluated using various common goodness of fit measures, i.e., the ratio of chi-square ($\chi2$) statistics to the degree of freedom (df), CFI, normed fit index (NFI), GFI, adjusted goodness-of-fit index (AGFI), and root mean square error (RMR) of approximation (RMSEA). The observed normed ($\chi2$/df) for this model was established to be (1.399) with p-value (0.063 > 0.05) which meets the terms with the requirement of < 3 as shown in Table 4. The overall indicators show that the model is a good fit with NFI = 0.948, RMR = 0.032, CFI = 0.908, GFI = 0.938, AGFI = 0.921, and RMSEA = 0.034.

TABLE 4 STATISTICAL STRUCTURAL INDICES OF SEM MODEL

S. no.	**Parameters of statistics**	**Short name of parameter**	**Structural model**	**Recommended values for good fit**
1	Chi square	$\chi2$	116.177	-
2	Probability level	P	0.063	≥ 0.05
3	Degree of freedom	df	83	-
4	Observed normed	$\chi2$ /df	1.399	≤3.00
5	Normed fit index	NFI	0.948	≥ 0.90
6	Root mean square residual	RMR	0.032	≤ 0.05
7	Comparative fit index	CFI	0.908	≥ 0.90
8	Goodness of fit	GFI	0.938	≥ 0.90
9	Adjusted goodness of fit index	AGFI	0.921	≥ 0.90
10	Root mean square error of approximation	RMSEA	0.034	≤ 0.05

F. *Findings related to hypothesis*

Figure 3 presents the results of the three hypothesized relationships, i.e., H1, H2 and H3. The direct structural effect of DI has a significant and positive impact on DVH. The results show that H1 is not rejected which states that DI has an enhancing and significant effect on DVH. The standardized coefficient is 0.62, which is statistically significant at $p < 0.01$.

The direct structural effect of DI has an enhancing and significant impact on ET. The outcome revealed that H2 is not rejected and DI has an enhancing and significant effect on ET and standardised coefficient is 0.76.

There is a direct structural effect of ET on DVH (0.70), thereby hypothesis H3 is not rejected. DI enhancing ET (0.76) relates to offshore outsourcing, and ET is enhancing DVH (0.70). These results suggest that DI enhances barriers to reconfigurable manufacturing systems related to ET and also enhances DVH.

Results of the SEM model recommend that DI contributes significantly towards enhancing ET and DVH. Now, examining the loadings on the main dimensions of DI, difficulty in software interface (structural loading = 0.87) is the main cause which enhances DI. Loading of the main dimension of ET is time spent on tooling (structural loading = 0.81). Part variety handling (structural loading = 0.67) is the main dimension for DVH. Results of the hypothesis tests are presented in Table 5.

Figure 3 Structural equation model for DI, ET and DVH

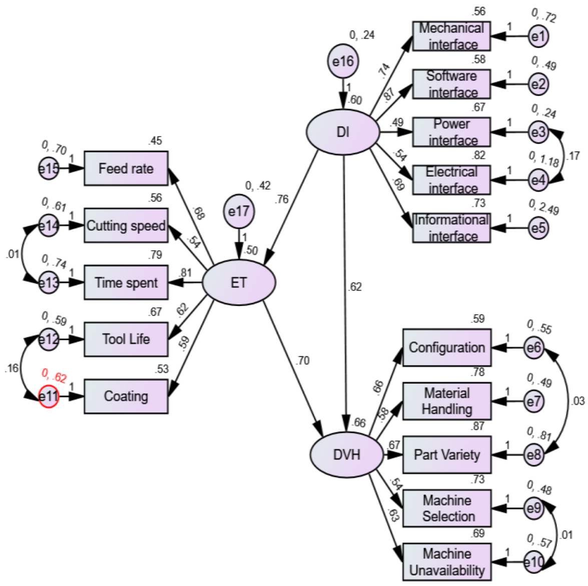


TABLE 5 RESULTS OF THE HYPOTHESIS TESTS

Hypo thesis	**Description**	**Standard regression weight**	**Inference drawn**
H1	Difficult interface has a positive and significant effect on the difficulty in variety handling.	0.62	Supported
H2	Difficult interface has a positive and significant effect on expensive tooling.	0.76	Supported
H3	Expensive tooling has a positive and significant effect on difficulty in variety handling.	0.7	Supported
H0	The overall hypothesis model has a good fit.	Model meets the recommended values, i.e., NFI=0.948, GFI=0.938, CFI=0.908, AGFI=0.921 and RMSEA=0.034	Supported

IV. CONCLUSION

DI, ET and DVH are the three important dimensions of the RMS addressed in this paper with an aim to support the transition from traditional manufacturing system to RMS. This study makes use of the SEM to investigate and establish the structural relationship between DI, ET and the DVH. The empirical findings from the study shows that less complexity in DI can improve firm's ET and DVH, which otherwise gets impacted in a negative way.. Following conclusions can be made from the study.

- DI has a positive effect on the DVH implying that simpler interfaces bring an ease in handling the outputs from the RMS.
- ET is significantly impacted by DI. This means that ET to produce more kinds of outputs, the tooling involved is expensive and the RMS interface gets difficult for the operator. This suggests, to some extent, that DI plays a vital role in RMS.
- ET has a statistically positive effect on DVH.

The study has numerous implications. It is the only study which endeavours to examine the relationship between the dimensions of DI, ET and DVH in manufacturing. The findings will help decision makers to know the significance of DI metrics and how DI metrics manage ET and DVH. This study has some limitations that would provide an opportunity for further research. Firstly, this study is exploratory in nature and examination of additional factors (size of the company, type of operations, field of operations i.e., industrial or service sector, etc.) which are not included in the model will provide an opportunity for further research. Secondly, the study can be extended to other industries which have already adopted RMS and are struggling to be more efficient. Further research, including complete analysis, can surely provide ways to increase efficiency.

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