Almannai, B., Greenough, R.M. and Kay, J.M. (2008), 'A decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies', *Robotics and Computer-Integrated Manufacturing,* published online, Vol. 24, No. 4, pp. 501-507

Title:

A decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies

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Abstract

With the advent of the new challenge to design a more lean and responsive computer-integrated manufacturing system, firms have been striving to achieve a coherent interaction between technology, organisation, and people to meet this challenge. This paper describes an integrated approach developed for supporting management in addressing technology, organisation and people at the earliest stages of manufacturing automation decision-making. The approach uses both the quality function deployment (QFD) technique and the failure mode and effects analysis (FMEA) technique. The principal concepts of both applications are merged together to form a decision tool; QFD in its ability to identify the most suitable manufacturing automation alternative and FMEA in its ability to identify the associated risk with that option to be addressed in the manufacturing system design and implementation phases. In addition, this paper presents the results of a practical evaluation conducted in industry.

Keywords: QFD; FMEA; Decision-making; Manufacturing systems; Automation; Man-machine interaction

1. Introduction

Today the manufacturing world is facing major pressures due to the globalisation of markets. Internal and external organisational pressures have led to increased competition, market complexity, and new customer demands. It has been noted how organisations adopt lean or agile manufacturing strategies to overcome this problem [1]. These strategies have different approaches and elements to address in the design of the manufacturing system, but they all depend on two common things: acquiring technology and the effective operation of this technology by humans.

Developments in computer-integrated manufacturing systems and the methods by which they are designed have induced firms to shift their emphasis towards human factors, particularly man-machine interaction, and to consider people as assets instead of costs.

In the manufacturing systems design literature, emphasis is directed towards producing a coherent interaction between technology, organisation, and people to overcome new competitive challenges. Various authors have pointed out the importance of addressing human factors generally in the evaluation and design of manufacturing systems, calling specifically for the adoption of a balanced method based on technology, organisation, and people [2,3,4].

Furthermore, the literature on investment evaluation is continuously being updated to accommodate the new market demands and manufacturing technology [5]. The changes in the market environment and justification of new manufacturing technologies have caused management to shift away from relying on traditional economic justification to the incorporation of intangible benefits and organisational strategy [6]. However, there continue to be reports of investment failures and difficulties in computer-integrated manufacturing systems implementation, due to the lack of addressing man-machine interaction appropriately [2,7].

Moreover, an investigation into human factors and manufacturing automation clearly illustrated that despite managers' interest in having a balanced consideration of both technology and humans in the planning and designing of their manufacturing system, and their efforts in placing more emphasis on the importance of human elements in the manufacturing environment; in practice they were still not appropriately considering man-machine interaction in their manufacturing automation decision-making [8]. In addition, it was noticed that management needed to be supported in improving man-machine interaction at the earliest stage of their manufacturing automation decision-making process, in order for them to avoid the pitfalls of over-automation which can lead to the failure of computer-integrated manufacturing systems to deliver cost effective and flexible operations.

In an attempt to respond to this, a decision tool for the integration of technology, organisation and people during the automation decision-making process has been developed. The decision tool uses the QFD technique to link management's automation investment objectives with technology, organisation, and people evaluation to determine

the best alternative. Thereafter, the FMEA technique is deployed to draw attention to any problems that might be associated with that option in terms of design and implementation.
This paper describes the approach and the results of an evaluation in industry. It is organised into five sections. Section 2 contains a general view of the developed method while Section 3 describes the technique in detail; the methodology is applied in a real case in Section 4 followed by a discussion in Section 5 and conclusions in Section 6.

2. The Approach

The consideration of technology, organisation, and people issues in manufacturing automation investment is an activity that requires the evaluation of both tangible and intangible elements. The QFD method not only allows the consideration of both tangible and intangible elements, but also the identification of the importance of each of these elements in the decision. However, there are situations when taking a decision could result in accepting some trade-offs, and it becomes an obstacle for managers to revisit and plan for them in the implementation stage. Therefore, an extra technique (FMEA) was appended to highlight any related trade-offs or areas of concern for implementation review.

Rather than the traditional investment justification process, the proposed methodology uses the QFD technique as the prime method to link the automation investment objectives with technology, organisation and people evaluation for the selection of the best alternative. Subsequently, the decision is fed into the FMEA technique to highlight the related potential problems associated with it. The combination of the QFD and FMEA techniques shown in Figure 1 represents an outline of the developed methodology concept.

2.1. Quality Function Deployment Review

The Quality Function Deployment (QFD) technique is a systematic procedure for defining customer needs and interpreting them in terms of product features and process characteristics. The systematic analysis helps developers avoid rushed decisions that fail to take the entire product and all the customer needs into account [9]. It is a process that involves constructing one or a set of interlinked matrices, known as 'quality tables'. The first of these matrices is called the "House of Quality" (HOQ). The house of quality matrix has two principal parts; the horizontal part, which contains information relevant to the customer, and the vertical part, which contains corresponding technical translation of their needs [10]. The basic process underlying QFD resides in the centre of the matrix where the customer and technical parts intersect, providing an opportunity to examine each customer's voice versus each technical requirement, for a detailed description of QFD formation process [9].

The proposed methodology uses this concept to capture the automation investment objectives and link them with technology, organisation, and people evaluation criteria for the selection of the best alternative. Therefore, in this methodology rather than listing the design requirements along the top portion of the HOQ matrix the automation investment evaluation criteria are listed. The relationship examination allows management to examine each automation investment objective against the evaluation criteria, as well as identifying the importance of each evaluation criterion. Thereafter, a second house is used to identify the most appropriate automation alternative. Therefore, rather than listing the part/subsystem requirements along the top portion of the second matrix the automation alternatives are listed. The relationship examination allows management to examine each automation alternative against the evaluation criteria (input from HOQ) to identify the most appropriate option.

However, as in any evaluation process, there are situations in which making a decision involves trade-offs to reach a satisfactory outcome, and it becomes necessary for managers to revisit these trade-off decisions in the implementation stage. Therefore, interlinking the QFD with the FMEA technique was felt to be necessary to highlight any related trade-offs or areas of concern which might require a review of the design and implementation.

2.2. Failure Mode Effects Analysis Review

Failure mode and effects analysis (FMEA) is a disciplined approach used to identify potential failures of a product or service and then determine the frequency and impact of the failure. It is an approach that is often referred to as a "bottom up" approach, as it functions by means of the identification of a particular cause or failure mode within a system in a fashion that traces forward the logical sequence of this condition through the system to the final effects [11]. The main idea is to generate a risk priority number (RPN) for each failure mode. The higher the risk number, the more serious the failure could be, and the more important it is that this failure mode be addressed. For a detailed description of the FMEA creation process, see [11].

The proposed methodology uses this approach to identify the risks associated with the best alternative selected to avoid unforeseen problems following the installation and operation stages. Therefore, rather than the standard application for identifying potential product failures and preventing them, it is applied to support management in identifying potential problems with the selected alternative and preventing them. In addition, establishing the risk priority numbers allows management to determine the importance of addressing potentially troublesome areas for recommendations and future review.

2.3. Development of the Decision Tool

In order to deploy the QFD and FMEA techniques in the proposed structure, certain modifications were necessary. The techniques are deployed in a non-product application, specifically, in automated manufacturing systems selection and risk assessment processes. Therefore, certain parts from the basic structure had to be either renamed or omitted.

The House of Quality correlations matrix, the planning matrix and the technical & target analysis parts were not deployed in this methodology; as such investigations were not considered relevant for this decision-making process. In addition, two major steps were removed from the basic FMEA application to enable this technique to be applied in a

non-product context. These steps were 'assigning detection ratings' and 'calculation of new risk priority numbers', both of which were felt to be much less relevant outside the product design context [13].
The modifications were conducted after a literature review of both QFD and FMEA non-product applications demonstrated feasibility of carrying out these alterations [5,12,13].

Moreover, what is essential besides the mechanism process was to determine the evaluation criteria and sub-evaluation criteria against which the manufacturing automation options will be evaluated. The process of identifying the evaluation criteria and sub-evaluation criteria involved compiling a list of the elements that could be related to technology, organisation, and people in manufacturing systems selection and design literature. In addition, both the evaluation criteria and sub-evaluation criteria were assessed against predetermined criteria to enable a robust selection process. The selection process was carried out through a screening process using the following three criteria:

1 General relevance: evidence that both the evaluation criteria and sub-evaluation criteria are related to manufacturing systems selection or design process.
2 Specific relevance: evidence that both the evaluation criteria and sub-evaluation criteria specifically relates to either the evaluation or the implementation process.
3 Credibility: a minimum of three sources must agree that each criterion is an essential factor to consider in manufacturing systems evaluation or successful implementation process. However, for the sub-evaluation criteria a minimum of three sources must indicate that it is an essential factor in addressing each criterion.

3. The Decision-Making Framework

The proposed concept involves constructing a joint QFD and FMEA model. Both techniques are used to support the manufacturing automation decision-making process.

Consequently, they need to be incorporated into a framework and a layout which is developed specifically for this purpose. In this framework the QFD process involves creating two interlinked matrices. The first matrix starts with the management and their needs and relates their needs to system evaluation criteria. The second matrix follows through the evaluation criteria (inputs) and magnifies them into sub-evaluation criteria for selection of the best alternative (outputs). The selected alternative evaluation data is then fed into the FMEA to conduct a risk assessment, as shown in Figure 2.

Stage 1: Linking Automation Investment Objectives with Evaluation Criteria

The purpose of the first stage is to determine the importance of the evaluation criteria in relation to management's needs. The user gathers and prioritises the automation investment objectives from the stakeholders involved in the investment. The user then enters the data into the QFD matrix to establish relationships between the needs and the evaluation criteria. The matrix computation will enable the user to realise how much influence each evaluation criterion will have on the decision-making process, as shown in Figure 3.

Stage 2: Automation Alternative Selection

The purpose of the second stage is to identify the best alternative. In this stage the results are transformed from the first QFD matrix to the second matrix to drive the sub-evaluation criteria importance ranking. The second matrix computation will enable the user to evaluate the alternative options against the sub-evaluation criteria, in order to identify the most suitable option, as shown in Figure 4.

Stage 3: Decision Assessment

The purpose of the third stage is to identify the risks associated with the best alternative. In this stage the best alternative evaluation data from the second QFD matrix is transferred to the FMEA worksheet to indicate any potential problems. Any negative scores within the data are used to highlight the potentially troublesome areas for special attention, as shown in Table 1. The outcome from this final stage is represented by a set of normalised risk priority numbers (RPN) for each element calculated from the averages of the RPNs for each associated sub-element. These, in turn, have been calculated for each sub-element by multiplying the severity of each potential problem by its likelihood of occurrence.

4. Assessment of the Decision Tool in Industry

The proposed decision-making tool was produced as an Excel spreadsheet supported by a paper workbook. The industrial assessment process was split into two stages; industrial trial evaluation and practical application. The intention of the industrial trial evaluation was to seek expert opinions and to identify any problems and difficulties with the developed decision tool prior to direct application in the case study. The practical application, on the other hand, was conducted to observe the application of the methodology in practice in order to evaluate whether it is workable, gives a useful output, and practical.

4.1. Trial Evaluation

The industrial trial evaluation was conducted in four organisations, two from the aerospace industry, one from the automotive industry and an automotive component manufacturer. The participants were asked to have a trial interaction with the decision tool, to explore the stages and steps of the decision and assessment process. Thereafter, a demonstration run was performed followed by a questionnaire. The outcome of this examination was very valuable as it ensured face validity and led to constructive alterations.

4.2. Practical Application

The case study adopted for the practical application was based on the latest equipment selection and acquisition process performed at the seals division at Rolls-Royce compression systems plant in Inchinnan; the selection and acquisition of eight chip forming machines. The application was structured as follows: one day to conduct the first and second stage of the decision process (linking automation investment drives

with evaluation criteria and automation alternative selection), and on the second day to conduct the third stage (decision risk assessment).
Moreover, an evaluation questionnaire was used to guide the assessment process during and after the practical application, and a diary was used to capture any comments and note observations. The questionnaire was categorised into four sections to reflect the assessment methodology. The first three sections were designed to assess the feasibility and usability at the end of each stage in the decision tool, and the final section was designed to assess the feasibility, usability and usefulness of the overall process and approach [14, 15]. Sample questions used were "Overall, did you find the methodology easy to follow? If not, could you state why not?" and "Did you find the tool to be user-friendly and clear? If not, could you state why not?" The full questionnaire can be found in [16].

4.3. Results

The feedback gathered from assessing linking automation investment drivers with evaluation elements stage demonstrated the feasibility and usability of the first part of the methodology. Overall, the user was able to follow the instructions and determine the weighting of the evaluation elements with contentment. The user's comment was "I am quite happy with what I have seen and done." In addition, the user realised the importance of utilising the investment drivers to determine the weighting of the evaluation elements. In the Rolls-Royce decision-making process the technical and commercial evaluation attributes are considered as equal, which is questionable.

Moreover, the feedback gathered from assessing automation alternative selection stage demonstrated the feasibility and usability of the second part of the methodology. Overall, the user was able to follow the instructions and score the automation alternatives against the sub-evaluation elements without any difficulties. This stage of the process is similar to the Rolls-Royce decision-making process, which involves technical and commercial evaluation attributes that are rated according to a scale. In addition, the best automation option identified from the automation alternative selection stage was the same as the historical outcome of the Rolls-Royce decision-making process.

The feedback gathered from the decision risk assessment stage demonstrated the feasibility and usability of the final part of the methodology. Overall, the user was able to follow the instructions and determine the associated risk with the selected automation alternative with simplicity. The user analysed the risk associated with the issues that were negatively rated during the evaluation. In addition, the user carefully examined the issues that did not receive the highest rate of acceptance, and report the risk that could be associated. However, the user pointed out that there should be a pop-up message asking to confirm data deletion when the reset option is selected, in order to avoid accidental data loss.

Finally, the usefulness of the solution was understood by the user who pointed out that the decision tool enabled users to consider and address people issues appropriately. In addition, the user did not think using the tool would make a better decision, commenting "Overall I think we have got the same result." However, the user noted that the preparation and implementation would have been enhanced. The user's comment was "Ultimately it lays out the risk areas and therefore starts making your project plan. It makes you think how to mitigate the risk associated." In addition, the user stated the following with regards to the evaluation criteria "in the categorisation it gives a good guide to look at other areas you might not necessarily consider."
Furthermore, the weakness reported in comparison to the Rolls-Royce decision-making process was that it is more time consuming.

5. Discussion

This research is based on academic literature and industrial survey [8]. The aim was to develop a tool that would incorporate human factors in the evaluation of different automation alternatives at the manufacturing systems design stage. The potential benefit of the tool is an improved balance between the relative importance of technology, organisation and people at the earliest stages of manufacturing automation decision-making. This will improve the design and implementation processes for manufacturing systems.

Accordingly, what has been described earlier is a framework that was devised to achieve this task. This decision-making framework was based on the deployment both the quality function deployment (QFD) technique and the failure mode and effects analysis (FMEA) technique. The decision-making and assessment criteria incorporated were designed to ensure that the right proportions of technical, organisational, and people issues are reviewed in the process. They specifically address strategic, financial, organisational, technical, integration, safety, and human factors.

In addition, the developed decision tool was evaluated in industry, through evaluation by demonstration and practical application. The evaluation by demonstration outcome resulted in positive feedback and constructive comments. Furthermore, the developed decision tool was tested using real data and gave valid output. The best alternative suggested for the case study was the same as the Rolls-Royce decision-making outcome. With the benefit of 6 months' hindsight the participant was able to claim that the Rolls-Royce decision making process had led to the best outcome. The tool described in this paper would also have suggested this outcome. This result support the view that the new developed decision tool is at least as valuable as Rolls-Royce's existing process. Moreover, the participant indicated extra benefits of the new tool.

The decision tool highlighted various people issues that were not considered in Rolls-Royce decision-making process and further analysed them in the risk assessment stage. The participant comment regarding this issue "in the categorisation it gives a good guide to look at other areas you might not necessarily consider." In addition, it not only assisted in human factors incorporation alongside technical and organisational factors at the initial stages of technology selection, but as well set out the risk areas and supported mitigating them.

Furthermore, the weakness indicated in Section 4.3 might not be considered as a drawback. Even though the user stated that the tool consumes more time than the existing Rolls-Royce decision making process, it was added that this is not really a weakness as such decisions would require such assessment.

Overall, the authors find the industrial evaluation feedback to be positively encouraging. However, as in any research, the more cases are used for the testing of the developed solution, the more precise the conclusion will be. The authors are conscious that the practical application was performed in a single case study, and there is a need to perform more industrial applications to permit greater understanding of the decision tool's strengths and weaknesses in terms of execution and performance.

6. Conclusion

The objectives of this paper were to highlight the importance of having a balanced consideration of technology, organisation, and people issues in manufacturing automation investment, and to present a decision methodology that addressed this issue. This paper has described the development of a manufacturing automation decision support tool that is intended to support management not only in improving their decision by addressing the right proportions of technical, organisational, and people issues, but also to be prepared for implementation and operation unforeseen problems. Furthermore, the results from a practical application in industry were presented. Overall, the results demonstrated the feasibility, usability, and usefulness of the proposed methodology.

Future work needs to be done to further assess the benefits and weakness of the method proposed. Another interesting extension for this research would be the application of this methodology in other areas of the manufacturing decision-making process, such as manufacturing process selection.

Acknowledgements

The authors wish to acknowledge the support of Rolls-Royce UK, particularly the senior manufacturing engineers at the Inchinnan plant for their help in this research.

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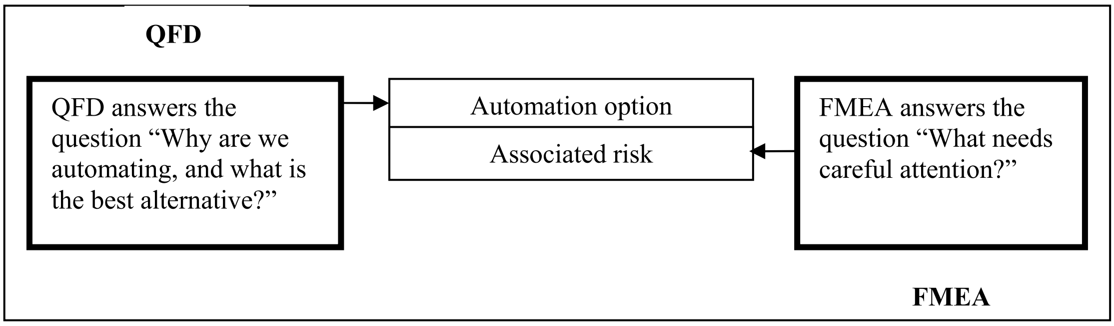

Figure 1: Manufacturing automation decision tool concept

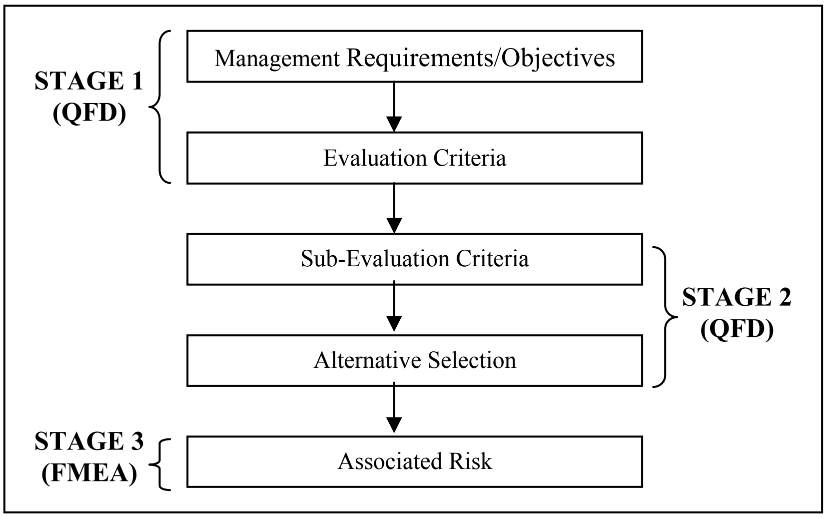

Figure 2: Decision-making framework

Help		Evaluation Elements Description	Evaluation Elements							Reset Spreadsheet
		Automation Investment drivers	Strategic Justification	Financial Justification	Systems Integration	Technology & Organisation Integration	Technical Justification	Technology & People Integration	Safety Justification	Ranking of Importance
Requirements / Objectives	Strategic	Quality reputation	9				9			5
		Aspirational products	9		1	1	9			4
	Tactical	Reduce time to market	9		3	1	9	1		3
		Reduce unit cost	9	3	3		9	3		5
		Quick payback period	3	9						5
	Operational	Advanced CAD/CAM system			3		9			3
		Precision mouldings					9			4
		Hybrid automation in assembly			9	3	9	9		4
		Improve working conditions					1	9	9	2
		Total	168	60	73	19	254	72	18	
		Normalised	25.30%	9.04%	10.99%	2.86%	38.25%	10.84%	2.71%	

Figure 3: An example of linking automation investment objectives with evaluation criteria stage

Help		Sub-Elements Description	Manufacturing Automation Options					
	Elements	Sub-Elements	Option 1	Option 2	Option 3	Option 4	Option 5	Ranking of Importance
Evaluation Elements	Strategic Justification	Support short-term strategic manufacturing objectives	9	3	3			25.30%
		Support long-term strategic manufacturing objectives	9	3	9			
	Financial Justification	Acceptable economic justification results	3	-3	3			9.04%
		Accepable investment cost	9	1	3			
		Acceptable unit cost	9	9	9			
		Acceptable installation cost	3	-3	3			
		Acceptable operation cost	3	-1	3			
	Systems Integration	Feasable to integrate with existing manufacturing hardware systems	-1	9	1			10.99%
		Feasable to integrate with existing manufacturing software systems	3	9	1			
	Technology & Organisation Integration	Compatible with organisation work procedure	3	3	3			2.86%
		Compatible with organisation structure	3	-3	-3			
		Compatible with work group	-3	-3	-1			
		Compatible with personnel policies	-1	-1	1			
		Compatible with current job design	3	9	-3			
	Technical Justification	Acceptable productivity specifications	9	9	9			38.25%
		Acceptable flexibility specifications	-9	9	-1			
		Acceptable quality specifications	9	-1	9			
		Acceptable support and test equipment	3	-3	-3			
		Acceptable maintainability specifications	9	3	3			
		Acceptable technology supplier	9	-1	3			
		Acceptable longevity	3	9	3			
	Technology & People Integration	Machine workstation design specification compatible with user's physical characteristics	9	3	3			10.84%
		Machine physical workload specification compatible with user's physical characteristics	3	3	3			
		Machine mental workload specification compatible with user's mental characteristics	-1	-3	-3			
		User/machine interface specification compatible with user's physical and mental characteristics	3	3	3			
	Safety Justification	Comply with machinery safety regulations	3	1	3			2.71%
		Comply with work environment safety regulations	3	1	1			
		Total	18.74	11.06	11.66	0.00	0.00	

Figure 4: An example of automation alternative selection stage

Elements	Sub-Elements	Potential Problem	Potential Effects	Selected Option	Severity	Potential Causes	Likelihood of problem	Action & Responsibility	Normalised RPN
Systems Integration	Feasible to integrate with existing manufacturing hardware systems	Mismatch in cycle times	Flow obstruction	-1	5	Higher output rate	5	Add feed magazine	44%
	Feasible to integrate with existing manufacturing software systems								
Technology & Organisation Integration	Compatible with organisation work procedures								13%
	Compatible with organisation structure								
	Compatible with work group	Require changes in team	Resistance to new technology	-3	3	Fewer operators required	2	Relocate excess labour	
	Compatible with personnel policies	Additional skills	Lower quality	-1	3	Job rotation	3	Additional job training	

Table 1: An example of decision assessment stage