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Applying Quality Function Deployment for the Design of a Next-Generation Manufacturing Simulation Game*

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Simulation games have grown in use as a training and education tool over the last fifty years. This paper examines the requirements of next-generation manufacturing methods and ascertains target design values for a novel simulation game that illustrates issues of next-generation manufacturing. Quality function deployment (QFD) is a powerful tool for translating customer requirements into target design values of engineering characteristics. This paper uses QFD to obtain design parameters for the novel game. Identified key paradigm and system elements of next generation manufacturing are used as the customer requirements or 'Whats' in the QFD analysis. Engineering characteristics of games are used as the 'Hows'. Linear regression and multi-attribute value theory with linear programming is used to translate the voice of the customer into optimum target design characteristics.

INTRODUCTION

SIMULATION GAMES use simulations, as the name suggests, but it generally refers to activities where simulations are used for the primary objective of learning. More specifically, Greenblat says that the term game is applied to simulations that progress dependant on the players' decisions in the past and where the environment and the activities of participants have the characteristics of the game [1]. The three characteristics of simulation games are [2]:

1. Simulation games always reflect reality.
2. A simulation game is embodied in the form of social communication.
3. Simulation games require evaluation of reality together with self-evaluation and reflection.

While case studies also aim to provide an experience with reality, the uniqueness of simulation games is the incorporation of the time element. Simulations imitate the passage of time and the participants have to adapt and respond to the results of their past decisions.

PSYCHOLOGY OF EXPERIENTIAL LEARNING

The use of simulation games began to spread after the Second World War, notably to teach business management. The most popular of the early games was 'Top Management Decision Simulation', a board game developed by the American Management Association in 1956 [3]. The initial reason for using games was that it had enormous motivational advantages as it made the learning process more enriching and fun.

The notion of experiential learning is based on theories of cognitive and developmental psychology. Schön has defined experimental learning as 'a conception of reflection in action' [4]. Experimental learning helps develop skills that can be put directly into action. American psychologist Lewin developed this notion further when his experiment, on seeing how theory and practice can be integrated in a learning environment, revealed that learning was best facilitated in an environment where there was dialectic tension and conflict between immediate, concrete experience (i.e. reality) and analytic detachment (i.e. formation of abstract concepts and generalisations) [4]. In the fifties, French developmental psychologist, Jean Piaget's theory that proposed, intelligence is developed by experience and an individual's interaction with their environment rather than being an innate characteristic, was groundbreaking, as it challenged conventional theories in developmental psychology. He also stated that play and imitation were two important tasks that developed a child's intellectual capabilities. This last idea of imitation and play was one of the early driving forces for simulation games to be used in education [4].

In 1984, a psychologist by the name of Kolb suggested the notion of learning being a 'process whereby knowledge is created by the transformation of experience' [4]. According to Kolb, learning was a four-stage cycle where each stage was a

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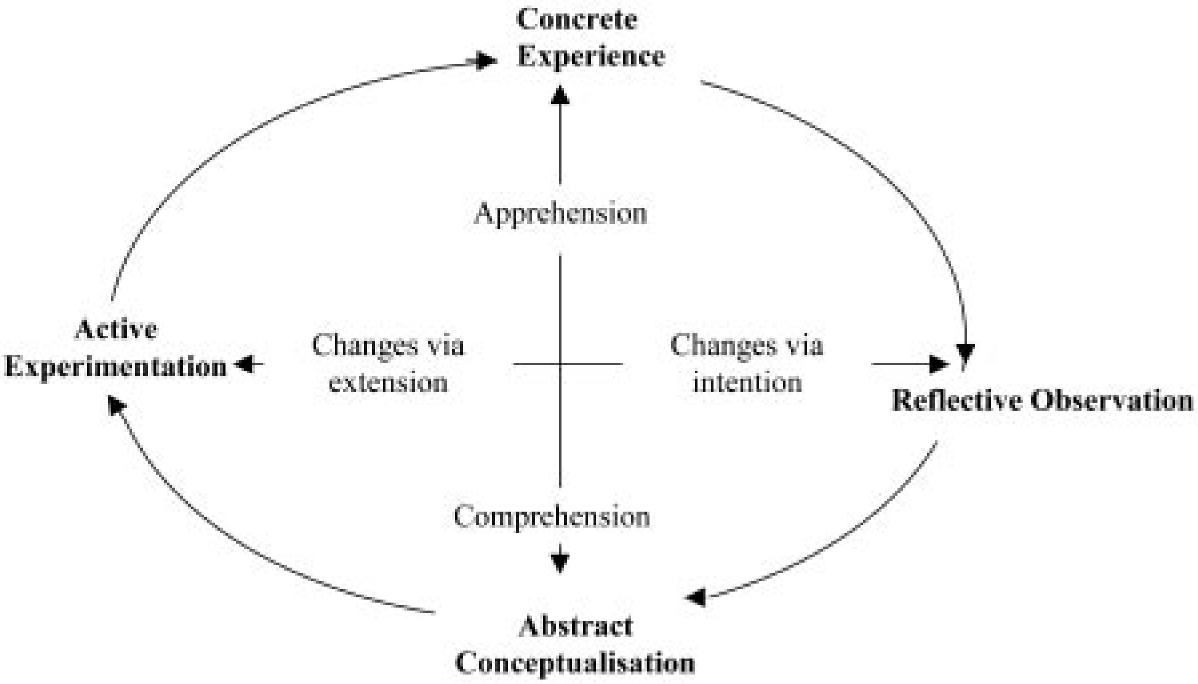

Fig. 1. Kolb's learning model.

learning mode (Fig. 1). Learning to be complete has to go through these four modes. The first stage is defined as **concrete experience** that involves incidents that happen to us or involve us. The second stage is **reflective observation** where we process what is happening to us. The third stage, involves developing, reflecting and storing abstract ideas about the outcomes and this stage has been defined as **abstract conceptualisation**. The final stage, namely the **experimental stage** helps the individual to draw on the ideas stored during the abstract conceptualisation stage along with the individual's skill set to face anticipated situations.

These theories are instrumental in providing a scientific explanation for the old quip 'learning by doing'. These also reaffirm the need for a learning tool like simulation games that allows the learners to experiment as well as get an idea of how things really work in an engineering context as today it is a common occurrence for decision makers to get caught up and carried away by buzz words without understanding the functional implications of these new management techniques.

REVIEW OF EXISTING GAMES

According to a UNESCO report in 2000, the number of simulation games used as learning tools has doubled over recent years [3]. The United States, United Kingdom and Finnish organisations are the most active users of simulation games as learning and process improvement tools. Today these simulation games are available in different media, namely, manual role-playing, computer-assisted and computerised.

A manual role-playing simulation game is generally a board game. It comprises a board with a few pieces that help the participants track their position and status with respect to a particular time. The game has a facilitator who generally follows a game script. The facilitator may at times introduce problems and surprises to encourage group participation and problem solving by bringing about a disturbance in the game flow. A good example of this type of simulation games is the Ogel Rowet—The Federal Mogul Business Game—a manufacturing planning and control game developed at Federal Mogul, with the objective of teaching participants how planning tools are integrated with the organisation of the manufacturing activity [5].

A computer-assisted role playing game, is generally a role-playing game with a script, but, where a computer is used to simulate the consequences of decisions made and to identify the participant's performance. The advent of computing technology has made this a very popular gaming media as the role-playing scripts allow these games to be flexible in their domain of applications. A typical example of this is the Chain Game developed at Waaginen University, Netherlands, that uses the Internet to allow players from all over the world to participate in gaming sessions that introduce them to the issues of supply chain management in the food industry [6].

A computerised game on the other hand is a computer-based simulation that runs the script of the game, introduces problems and calculates the consequences of decisions made. Basically, the computer provides the complete gaming environment. An example of this is the Enterprise game, a virtual reality simulation game being developed by SIMLAB, a simulation game research department at the Helsinki University of Technology. This game is being developed for employees of large organisations to understand how manufacturing processes are integrated in order to improve on overall performance. This game has been used successfully by ABB Industry Oy to increase individual knowledge on concepts of integration of the entire business function and to learn about the complex dynamics of products [7]. It should be mentioned though that there are many other computerised games that use less sophisticated visualisation technologies while providing a complete computerised gaming environment, yet these employ sophisticated game architectures and generally have longer lead times relative to computer-assisted and manual role-playing games. Moreover a computerised simulation game cannot be easily adapted in problem content to suit a specific organisations' training needs.

NEXT-GENERATION PARADIGMS

Rapid pace of change in the nature of manufacturing processes and systems coupled with dynamic business and socio-cultural environments has emphasised the need for developing a formal visioning methodology to predict the set of rules or paradigms that dictate the mindset in the future generation of manufacturing activities, in the United Kingdom and the global context. This is especially important in the design of the manufacturing simulation game as the objectives of the game are to meet the needs of next-generation manufacturing enterprises as well as to introduce higher education students to methods and concepts that will be of importance for next generation manufacturing.

Paradigm 1: A holistic model-driven manufacturing system

The Manufacturing Systems Integration Research Institute at Loughborough University, UK developed the holistic model. This approach requires the manufacturing enterprise to be considered simultaneously as a whole [8].

Pandya *et al.* [9] have outlined certain methodologies that can achieve these objectives:

1. The *order fulfilment process* that makes manufacturing enterprises customer-driven and flexible in terms of volume and variety in a highly dynamic market.
2. The *marketing process* that transforms information from customers, competitors and markets into market requirements in order to assist in better foresight of change in market behaviour.
3. The *technology management process* that transforms data from research and competitors into technology and process knowledge thereby creates an innovative and responsive climate. Also stress is laid on optimising the innovative process and this involves modelling tools to be used for strategic planning and design of activities. Moreover these tools are to use knowledge-specific to the organisation to enhance their validity.
4. The *support fulfilment process* that transforms the need for support and services into a product that continues to meet customer demands.

Paradigm 2: Parnaby's millennium approach

During the last two decades high capital investment has led to automating out the human factor in manufacturing without bringing conspicuous improvements in productivity due to added complexity and lack of strategic adaptation to technology. However this paradigm has also seen the development of cross-functional organisational design and control, move towards lean manufacture and emphasis on team-oriented change and improvement. To overcome the shortcomings and exploit the current potential, Parnaby [10] has suggested:

1. *Simultaneous engineering* involving simultaneous consideration of all aspects of businesses in project and product development.
2. *Effective management* of innovations and project development.
3. *Operational competencies* such as maintenance and supply chain management are as important as development competencies such as software decision systems and control systems.
4. *Training and development* of all employees with emphasis on techniques such as job rotation and teamwork along with developing their technical and management skills.
5. *Developing hard-to-copy competencies* and articulating accumulated knowledge specific to the organisation.
6. *Reducing complexity* by avoiding over-engineering of products and developing generic modular hardware, software and system designs. This would further encourage flexibility and reduce capital costs.

Paradigm 3: Post mass production paradigm

The post mass production paradigm is a notion developed by Tomiyama. It is 'a system of economic activity capable of encouraging and sustaining economic growth without depending on mass production and mass consumption' [11]. He studied the advances of manufacturing technologies namely miniaturisation and ultra precision of products and technologies, importance of homogenised management and control systems like quality control and identifies the 'evils' of mass production with regard to environmental damage and limited natural resources, wasteful innovation and complexity as well as trade frictions due the decreasing absorptive capacity of products in developed markets.

Hitomi [12] stressed that manufacturing has to be more human centred, environmental conscious and responsive to markets. In order to realise these objectives the suggested techniques are:

1. Greater consideration to *life cycle analysis* in design of products and emphasis on reclaiming and recycling artefacts, the costs of which are to be included in the product itself.
2. *Knowledge-intensive engineering* whereby existing knowledge is formalised and new knowledge is gained at various stages of operational activity such as marketing, design, production, maintenance, reclamation, reuse, recycling and discarding. This is seen as key for organisational survival as this knowledge at various stages of the product life cycle could be used to generate more value addition by improving the life span and reliability of products as well as aiding in product innovation.
3. *Human-centred organisational systems* promoting teamwork, flexible working and quality of working life as well as focused and integrated training and development of employees.

Paradigm 4: Ultimate manufacturing

Wah [13] addresses issues of rapid change in technology, market globalisation and corporate social responsibility. Innovation rather than productivity is seen as the main driver of growth in the manufacturing sector. Cost effectiveness by reducing lead times and efficient management of research, is also stressed, as flow of information rather than materials is seen as the key to survival in the future. In order to achieve this, the need for integration of human and technological systems is important while addressing broader social issues of distribution in the global context. In order to realise these objectives the following are suggested [13]:

1. Improved *customer responsiveness* by developing better logistic management technologies, obtaining real time knowledge from customers and customers' customers, low cost design of products capable of reaching the market quickly and the use of virtual management technologies to reduce the uncertainty of the environment in which organisations operate.
2. Stress on *global responsiveness* by globalising the organisations' economy and dispersing research and development geographically, in order to tap knowledge from all resources.
3. Improving *plant and equipment responsiveness* by minimising assets to meet existing demand, using leased and reconfigurable equipment to maintain flexibility, introduction of new technologies such as micro-machining and biotechnology, application of simulation techniques to

Table 1. Description of sub-criteria of different paradigms

Subcriteria	Description	PMPP	IMS	HOL	ULT	MIL
Reduced natural resources depletion	This indicates the necessity of a paradigm which causes the least depletion of natural resources available or uses renewable resources	VH	H	M	L	L
Recycling of wastes/products	This is a methodology for recycling the by-products of production as well as reusing extinct products to replenish natural resources	VH	H	L	L	L
Less waste generation	Reduced waste generation can be achieved using renewable resources or modifying manufacturing methods (e.g. biotechnology) so less waste is generated	VH	H	M	L	L
Longer product life cycle	Present trends indicate short product life cycles; the product is discarded before full utilization; this unnecessary wastage can be prevented	H	H	L	VL	L
Reduced product complexity	Unnecessary complexity makes the product less user-friendly and more difficult to maintain; it also causes more sophistication in customer demand	M	M	L	L	H
High productivity	This is the aim of every organization, but it should not be at the expense of quality	L	M	H	M	VH
Equipment responsiveness	To respond to the dynamic market, it is necessary that plant equipment and processes are capable of readily adapting to unexpected and rapid changes	M	L	L	VH	H
Process integration	This involves all processes being considered simultaneously in design and planning stages; it reduces uncertainties that may occur during implementation and production	M	L	VH	L	H
Equipment compatibility with existing systems	New equipment and systems should be implemented in stages so that existing systems can be upgraded or replaced with the passage of time; this reduces total down-time	L	L	H	VH	M
Modelling and simulation	Modelling techniques allow simulation of a manufacturing process before implementation and for monitoring it during operation	L	H	VH	M	L
Knowledge integration	Knowledge plays a crucial role in organizations; it must be fully integrated into manufacturing planning, control, design and research to achieve the optimum strategies	H	H	M	VL	L
Functional integration	Traditionally, enterprise management was less concerned with technology and research and development; it is necessary for all business functions to work together to formulate future strategies	VL	M	H	L	M
Employee skills	The rapid rate of technology advancement calls for greater skill capabilities; employees can be taught multidisciplinary skills through appropriate training and job rotation	M	H	L	L	M
Team-based approach	Decisions and strategic planning and control to be carried out in teams; future decisions will be more complex than today due to the technological and market changes	VH	M	L	VL	H

*PMPP, post-mass-production paradigm; IMS, intelligent manufacturing systems; HOL, holistic paradigm; ULT, ultimate manufacturing paradigm; MIL, millennium approach.

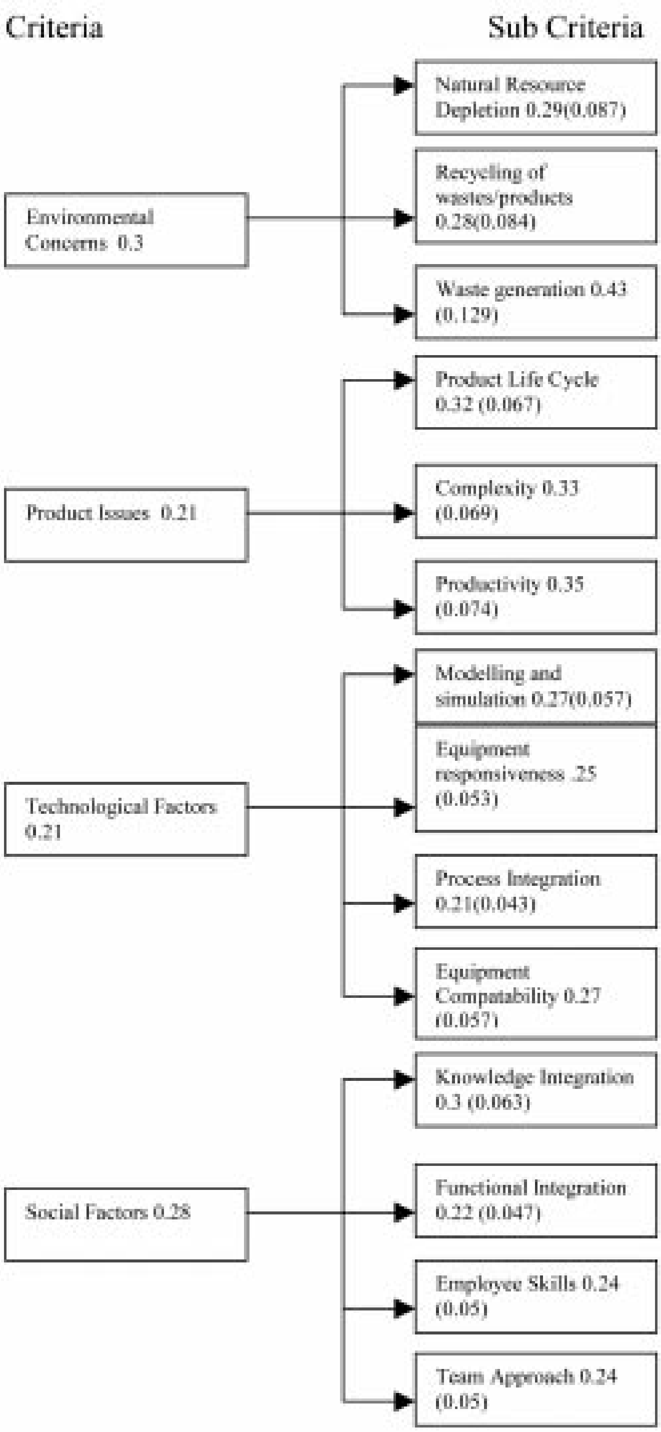

Fig. 2. Diagram showing criteria and sub-criteria and their relative weightings and absolute weights in brackets.

reduce uncertainty and elimination of expensive jigs and fixtures.

4. Improve *human responsiveness* by having a trained and multidisciplinary workforce who are creative and, by enhanced human machine interfaces, can promote human technical integration.

Paradigm 5: Intelligent manufacturing systems

The intelligent manufacturing systems (IMS) paradigm, stresses co-operation. This is a radical shift from the focus of the present economic system that encourages healthy competition. The rationale behind this is that co-operation will help normalise competition and at the same time address issues of wasteful new product development and encourage more responsible use of natural resources. Knowledge and its efficient management is also another key factor this paradigm highlights [14]. In order to realise these objectives the enabling methodologies being studied by the IMS Consortium [15] at present are:

1. Stress on product life cycle issues that emphasise optimum use of energy and materials, recyclability and reuse.
2. Development of clean and energy-efficient manufacturing processes, improvement in autonomy and flexibility of products and equipment as well as systemised technological innovation.
3. Increased use of strategy, planning and design tools like simulation and quality function deployment.
4. Collaborative research and development and formalisation of organisational knowledge in order to promote an environment of co-operation in the global economic context.
5. Improved image of manufacturing in the workforce by encouraging human centred organisational systems promoting teamwork, flexible working and quality of working life as well as focused and integrated training and development of employees.

Table 1 shows the main elements of next-generation manufacturing paradigms that were identified from the literature.

Reviewing previous and ongoing work on manufacturing paradigms was critical for determining training requirements for leaders of next-generation manufacture. A survey of engineers from industry and master level manufacturing students, the two target customer groups of this game, were carried out in order to identify elements of these paradigms considered crucial in next-generation manufacture. It should be mentioned that all the respondents had participated in sessions of Federal Mogul's Business Game conducted at UMIST, within a fortnight before the survey was conducted. The relative importance of the factors to dominate the next-generation manufacturing paradigm obtained from the survey are shown in Fig. 2.

THE FIRST HOUSE OF QUALITY DIAGRAM

Quality function deployment (QFD) was developed in Japan by Akao in 1972 as a way of matching customer attributes or preferences against engineering characteristics with the objective of systematically translating the 'voice of customer' through the stages of product planning, engineering and process design into a comprehensively specified product with defined engineering characteristics, process plans and process parameters [16, 17].

Quality function deployment is now widely used in a wide spectrum of industries, from manufacturing to services, over the world. The House of Quality (HoQ shown in Fig. 3), the initial process of QFD, is a formal articulation of engineering characteristics (the 'Hows') against performance characteristics or customer requirements (the 'Whats') [18]. The customer requirements were assessed through customer surveys. The engineering

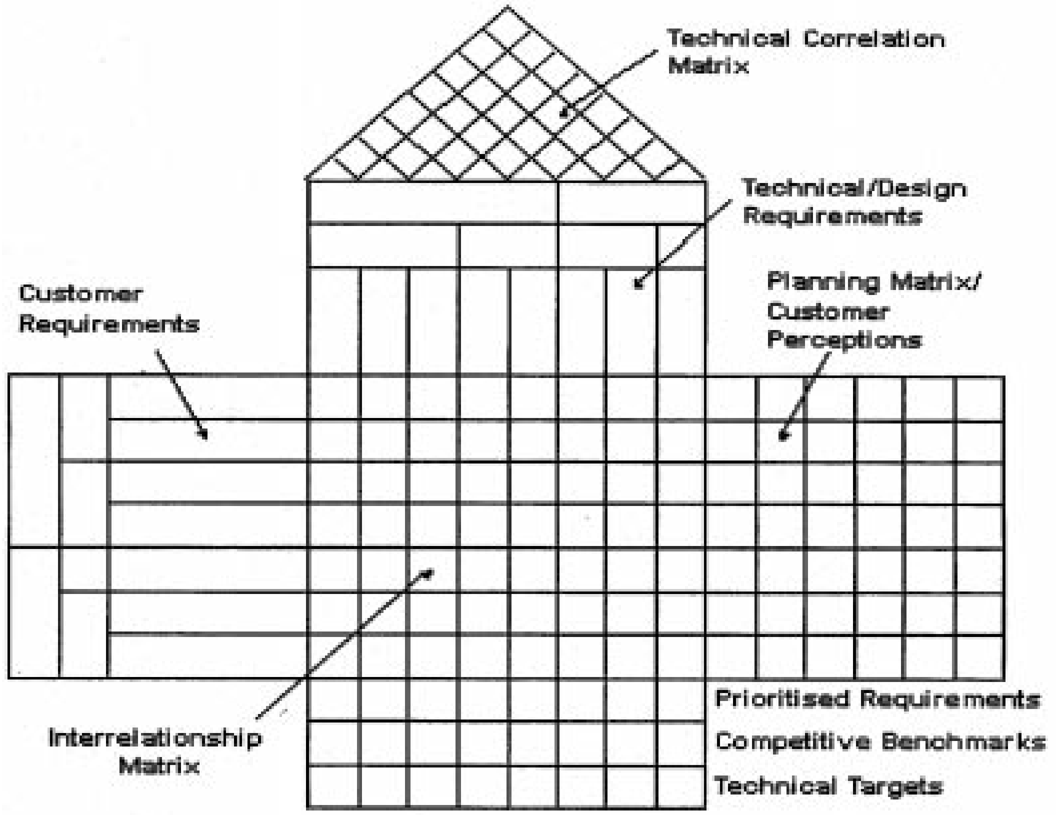

Fig. 3. Components of a House of Quality diagram.

characteristics include various factors that influence the performance characteristics. These were hard to quantify and hence a subjective user-defined scale was used. A relationship matrix is established to show the relationships between various engineering characteristics and performance characteristics. Finally there is a triangular matrix that contains the information on trade-offs between the different engineering characteristics. This can be continued to process planning and activity planning by making the 'Hows' from one stage into the 'Whats' of the next [19].

Determining the target values of engineering characteristics from the customer requirements is one of the essential outcomes of the QFD process. The determination of these in practice is generally done by seeing the position of the product against competitors and then using team consensus to set target levels [19]. However in the case of a large number of performance characteristics or engineering characteristics this becomes a lengthy and complicated process and does not necessarily result in optimum values, especially, if the standard deviations of the absolute levels of importance of the different performance characteristics are very small. This is the case with the House of Quality diagram in Fig. 4 where the standard deviation of the performance characteristics is 0.02 or 2%. Also the relationships between the characteristics are not known as the performance characteristics are linguistic and qualitative measures, whereas, the engineering characteristics are technical quantitative measures.

The proposed optimisation approach attempts to address these problems, by using multi-attribute value theory, combined with linear regression and linear programming, to determine the target values of engineering characteristics in the QFD process.

Let:

y_i = customer perception on level of performance for performance characteristics i. (where $i = 1, \ldots, m$);

x_j = target value for engineering characteristic j. (where $j = 1, \ldots., n$);

f_i = functional relationship between performance characteristic i and engineering characteristics, where, $i = 1, \ldots, m$. That is $y_i = f_i(x_1, \ldots, x_m)$;

g_j = functional relationship between engineering characteristic j and other engineering characteristics, where, $j = 1, \ldots, n$. That is $x_j = g_j(x_1, \ldots, x_n)$

In the model employed, the system parameters and constraints were assumed to have linear relationships, i.e. all the functions were assumed to be of order one, just as the equation below:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n \qquad (1)$$

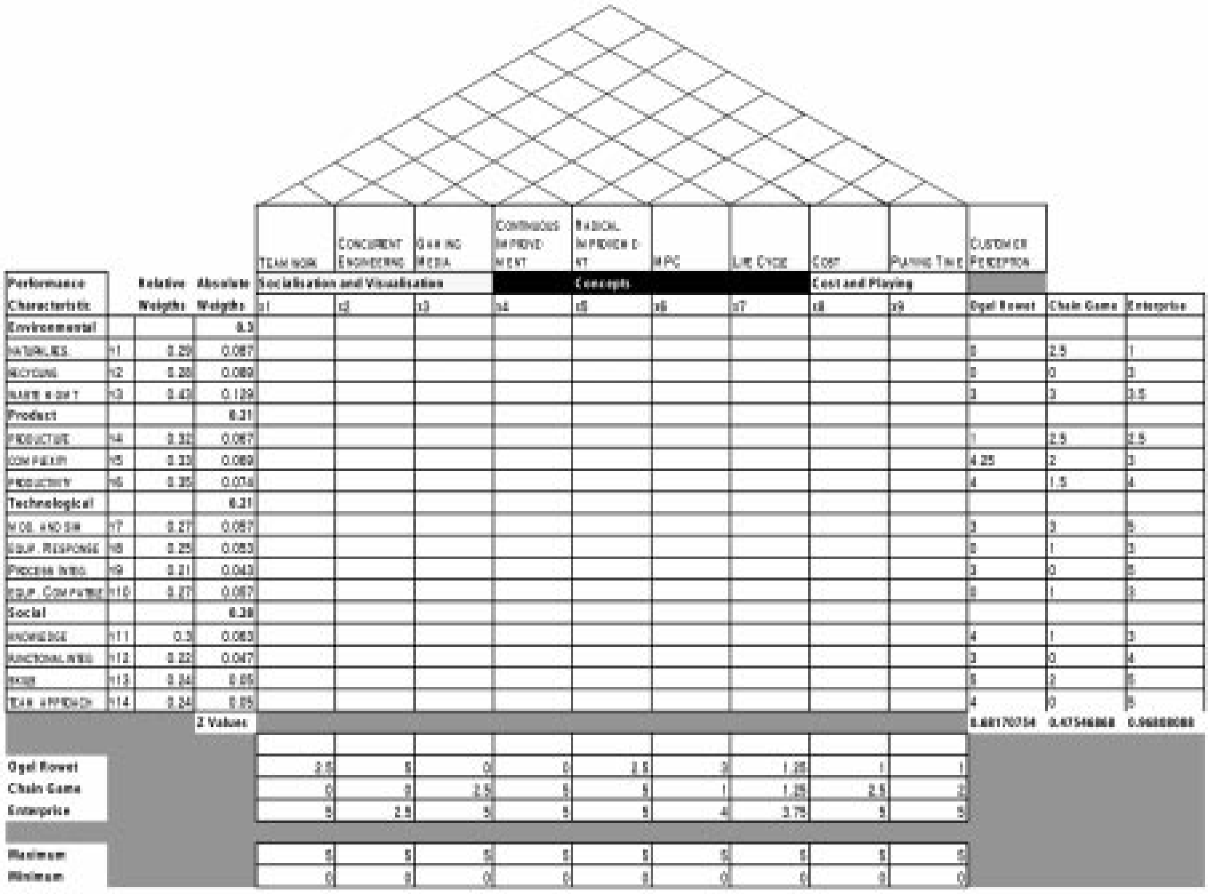

Fig. 4. First HoQ diagram.

Table 2. Z values for the games

Game	Z Value
Ogel Rowet	0.681708
Chain Game	0.475469
The Enterprise Game	0.968081
Target Game	0.849282

Hence, in accordance with this assumption, the linear regression method is used to determine the linear functional relationships, i.e. determine the values of $\beta_0, \ldots, \beta_n$. This was done for the kth observation for each set of data. The detailed method is outlined in Freund and Minton [20].

Once the linear relationships were computed using a simple programme on Mathlab, linear multi-attribute value (MAV) theory was used to define the crisp objectives. This provides the simplest way for modelling customer preferences for multiple performance characteristics with different weights [21].

Thus, the additive MAV function was used to obtain the overall level of customer satisfaction Z:

$$Z(y_1, \ldots, y_m) = \sum_{i=1}^{m} w_i V_i(y_i) \qquad (2)$$

Here $V_i(y_i)$ is the individual value function for performance characteristic i and w_i is the weight of performance characteristic i. The individual value function is scaled in such a way that $V_i(lowery_i) = 0$ and $V_i(uppery_i) = 1$, representing the lowest and highest possible values of y. Since y values are in a scale from 0 to 5, this condition could be simplified to:

$$V_i(y_i) = 0.2y_i$$

After the equation for Z was assessed, the problem could be simplified into a conventional linear program as below:

- *Objectives.* Find target values $x_1, x_2, \ldots, x_n$, which maximise overall customer satisfaction for $Z(y_1, \ldots, y_m)$.
- *Constraints.* Subject to: $y_i = f_i(x_1, \ldots, x_m)$; $x_j = g_j(x_1, \ldots, x_n)$.

It is imperative to note that Z is a function of y that in turn is a function of x. This represents a simple linear programming problem that can be solved using the solver on Microsoft Excel or other optimisers such as Lindo. Also it is important to specify the maximum and minimum values for all x_j. The values used for this model were taken from the House of Quality diagram figure.

The full linear formulation is thus generated using Microsoft Excel. The results of the Z values for the four games are listed in Table 2 and the target engineering characteristics are in Table 3.

DISCUSSION OF THE RESULTS

The target customer satisfaction level for the proposed design, the Z value, is approximately equal to 0.85 or 85%. This is lower than the customer satisfaction level obtained for the Enterprise Game, which is 0.96 or 96%. In this case of the Enterprise Game, the target design parameters as apparent from Tables 2 and 3, make for a design that will fill the gap in the market for a manufacturing training game. Moreover other resource constraints made a virtual environment option an unattractive route.

The scale used for socialisation and visualisation factors 3 translate into a value of approximately 2.5 in teamwork into a game where two teams compete against each other as opposed to a game where every participant plays individually (a value of 0) or a game where more than three teams compete against each other at a time (a value of 5). Also a value of approximately 2.5 in concurrent engineering refers to a game where half the decisions required to be made in a game involves cross-functional project teams as opposed to no cross-functional decision making (a value of 0) and cross-functional decision making in every decision (a value of 5).

The scale for gaming media used was a value of 5 for a completely computerised game where the facilitators function is incorporated into the game package, or a value of 2.5 for a computer-assisted game where computers assist visualisation, introduce problems to the participants and calculate performance but at the same time the whole learning process is carried out in the presence of a facilitator who at his or her discretion can introduce additional problems and discuss the learning objectives that were illustrated by the game. A value of 0 on the other hand was given to manual role-playing games. The target design value for the game indicates that customers prefer a computer assisted role-playing game. One of the

Table 3. Results of the linear programme formulation: the computed target values of the engineering characteristics for the new game

Teamwork	Concurrent Engineering	Gaming Media	Continuous Improvement	Radical Improvement	Manufacturing Planning & Control	Life Cycle	Cost	Playing Time
Socialisation and Visualisation				Concepts			Cost and Playing	Factors
x1	x2	x3	x4	x5	x6	x7	x8	x9
2.5286042	2.5230933	2.5055108	3.3212783	4.1624762	2.6727455	2.0853035	2.8330675	2.6712735

reasons cited by some survey respondents were that the human facilitator interaction was essential for summing up the issues illustrated and to remove any ambiguity about the rules of the game.

Cost target value was 2.8 and this was consistent with the scale where manual role playing games were given values between 0 to 1.5 depending on complexity and other factors, computer-assisted were given between 1.5 to 3 and computerised game got between 3 and 5. Also, a playing time of 2.67 translates into a game that is 9 hours long.

The concepts section in Table 3 show four possible areas that any next-generation manufacturing game must concentrate on. Next-generation manufacturing will face issues of manufacturing planning and control, life cycle analysis, continuous improvement and radical improvement as it needs to optimise and reduce waste in order to survive competition and dynamic business environments. However these four areas themselves encompass various business processes and functions and hence it became imperative to study next-generation systems in order to identify 'a group or combination of interrelated and interacting elements forming a collective entity' [22] of issues that the game needs to illustrate.

Literature on next-generation manufacturing systems generally stresses the importance of flexibility of technologies and organisational structures, autonomy and waste reduction [22–4]. Hence three manufacturing systems that were felt to withstand these challenges, namely, flexible manufacturing systems, reconfigurable manufacturing systems and holonic manufacturing systems, are discussed.

NEXT-GENERATION MANUFACTURING SYSTEMS

Flexible manufacturing systems

Slack *et al.* [25] have defined flexible manufacturing systems (FMS) as a 'computer controlled configuration of semi-independent workstations connected by automated material handling and machine loading facilities'. This system started gaining popularity in the early 90s. The component parts of a Flexible Manufacturing System are NC workstations, automated material handling, robotic loading and unloading facilities and a central computer control system that controls and coordinates the individual parts, production planning, and flow of material and information through the system. Hence FMS integrates many technologies into one self-contained system that can produce a wide variety of similar products in small batches without changeover delays. FMS can easily accommodate changes in design of products. This system thus has the overall impact of reducing lead-time, design costs, machinery operating time, product quality as well as reduction in personnel. However, high capital costs and floor space requirements are a few of the disadvantages of this system [23]. The costs benefits of this system are realised in its long-term application over several product life cycles. Many companies in competitive environments have adopted this system and it is expected that this system of manufacture will continue to be applied in manufacturing well into this century.

Reconfigurable manufacturing systems

Reconfigurable manufacturing systems (RMS) are defined as 'a system with adaptable, integrated equipment, processes and systems that can be readily reconfigured for a wide range of customer requirements for products, features and services' [24]. The component parts of RMS are NC machines with reconfigurable machine tools and controls in an open architecture environment that can accommodate technology upgrades. These generally include machinery made up of individual modules that can be combined together to form different types of machinery within a short period of time hence facilitating rapid changeover. The 'plug and play' nature of the modules is facilitated by standard power interfaces (electric units), mechanical interfaces (like gearbox drives) and software components (like control networks). This allows the machines to be customised to meet the ever-changing customer demands. In spite of this the machines can maintain high precision by using sensors for diagnosing and self-tuning.

This proposed system has many benefits over flexible manufacturing systems as it can accommodate technology upgrades within the system due to its open architecture characteristic as well as producing a wider range of products that do not have similar components or are not very similar. However, disadvantages with this system are that the high degree of flexibility leaves problems with product quality that arises out of human or material rigidities. Also modularity of the system makes it highly capital intensive and costly with benefits that are gained in the long term [23].

Holonic manufacturing systems

Arthur Koestler, a Hungarian philosopher, while talking about biological and social structures, says [26]:

> A 'part', as we generally use the word means something fragmentary and incomplete, which by itself would have no legitimate existence. On the other hand, a 'whole' is considered as something complete in itself. But wholes and parts in this absolute sense just do not exist anywhere, either in the domain of living organisms or of social organisations. What we find are intermediary structures, 'sub-wholes' that display some of the characteristics commonly attributed to the wholes and some of the characteristics commonly attributed to the parts.

He thus devised the word holons from the Greek words holos = 'whole' and the suffix 'on' meaning particle or part. This idea was taken by the Holonic Manufacturing Systems (HMS) consortium, a test case under the Intelligent Manufacturing Systems Research program in 1994 to define a holonic manufacturing system where a holon is 'an autonomous and co-operative building block of a manufacturing system for transforming, transporting, storing and validating information and physical objects' whereas a holarchy is defined as a system of holons that co-operate to achieve a goal or objective' [22]. The central theme to this proposed manufacturing system is co-operation between holons that stresses the need of efficient uses of resources and decision-making autonomy of holons. This makes the system highly resilient to external disturbances and highly adaptable. The structure of HMS is built around three basic holons namely:

1. *Resource holon* that comprises of the physical parts like production resources of a manufacturing system. This provides production capacity and functionality to the surrounding holons to drive production.
2. *Product holon* that contains the product and process knowledge to assure correct making of the product. This provides information to the other holons.
3. *Order holon* that is responsible for performing the assigned work correctly and on time.

These three holons are responsible for strategic, operational and enabling processes within the organisation. The three holons interact by exchanging information. The resource and product holon communicate process knowledge, product and order holons communicate production knowledge while resource and order holons communicate execution information (Fig. 5).

Aggregated holons are defined as a set of related holons that are clustered together and form a bigger holon with its own identity. Therefore an aggregation hierarchy is formed that is open ended at the top and bottom. This enables a holistic approach to manufacturing.

The benefits to this system are that it can be applied to almost any manufacturing setting unlike RMS and FMS that can be applied to manufacturing where there is a high variety of products with small batch volumes. This system is highly adaptive to change due to organised information flow but more research needs to be done into matters like integration of holons and methods to reduce lead times and changeover times.

THE SECOND HOUSE OF QUALITY DIAGRAM

Literature on these three next-generation manufacturing systems provided the 'Hows' or system characteristics for the next stage of the House of Quality (in Fig. 6) while the concepts used as the 'Hows' in the first House of Quality diagram, Fig. 4, form the 'Whats' in this stage. The other 'Hows' in Fig. 4 were not used as they translated directly into well-defined target design parameters. The House of Quality Diagram for the target system characteristics is shown in Fig. 7.

Multi-attribute value theory along with, linear regression was used just as had been done for the first House of Quality diagram above**.**

Table 4 shows the customer satisfaction levels, the Z values, for the target game as well as the other three-competitor games. Once again the Enterprise game scored highest in terms of customer satisfaction but due to time and resource constraints the results thus obtained were seen to suffice the objectives of this project.

Table 5 shows the target system characteristics values obtained and these were normalised and their percentage distribution was found, i.e. the distribution of problems in the games.

The results were then validated using a focus group of five. The focus group comprised of students and engineers from industry chosen randomly for the set used for the earlier survey (Fig. 2). The solutions were discussed in detail and necessary changes were made in the specification. The results obtained using multi-attribute value theory were found to be satisfactory and only few

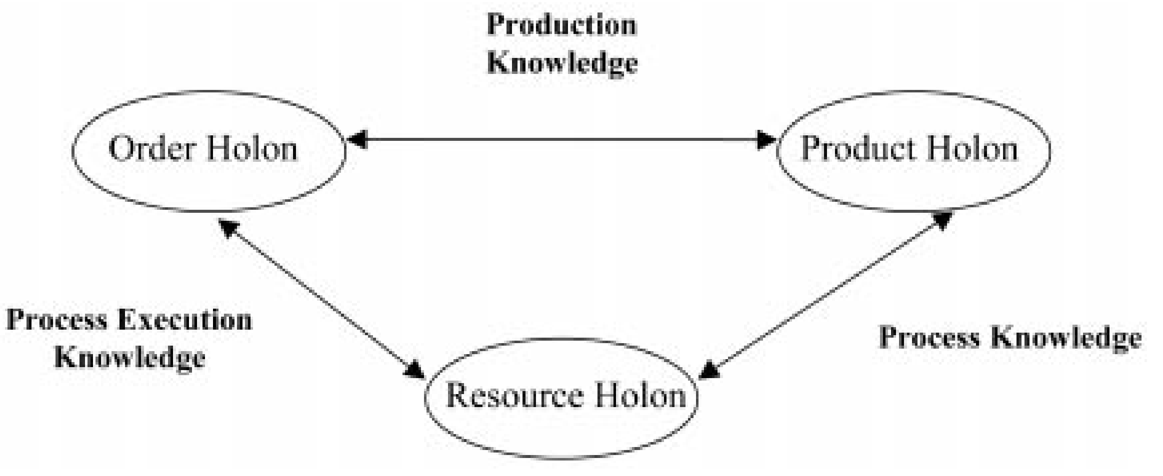

Fig. 5. Communication between holons in holonic manufacturing systems.

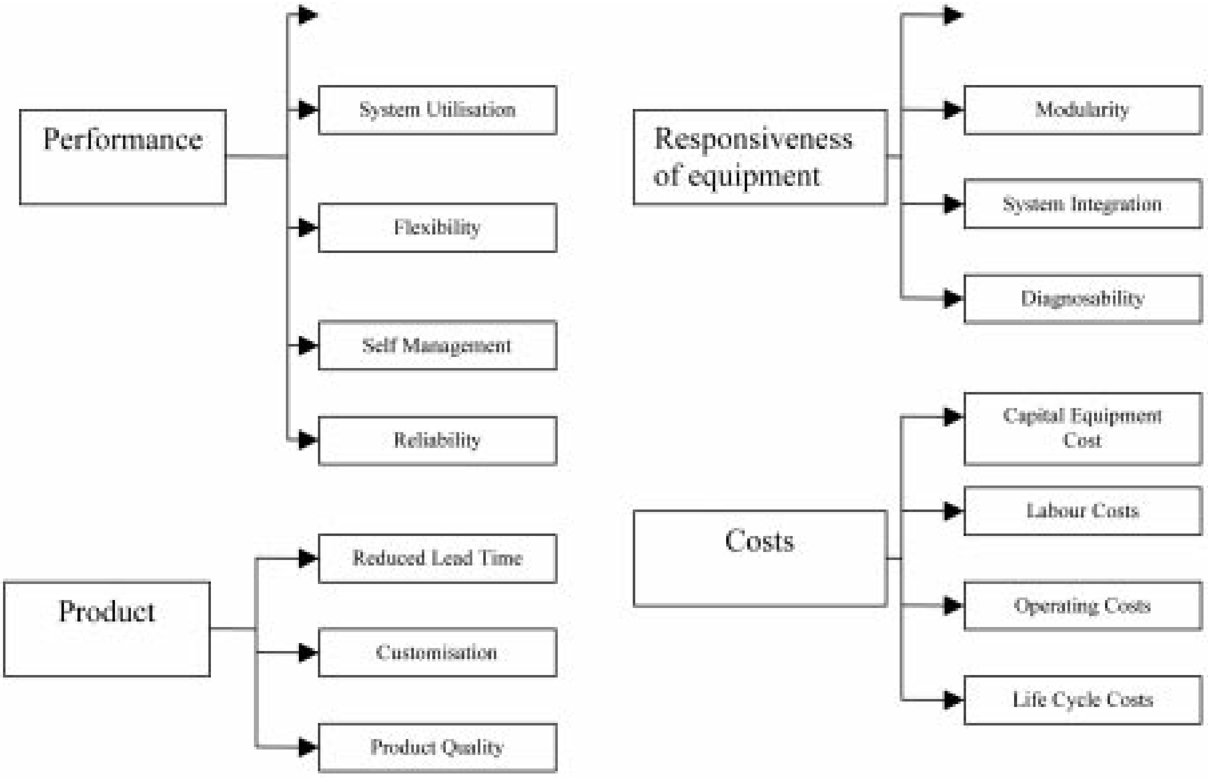

Fig. 6. The 'Hows' in the House of Quality diagram.

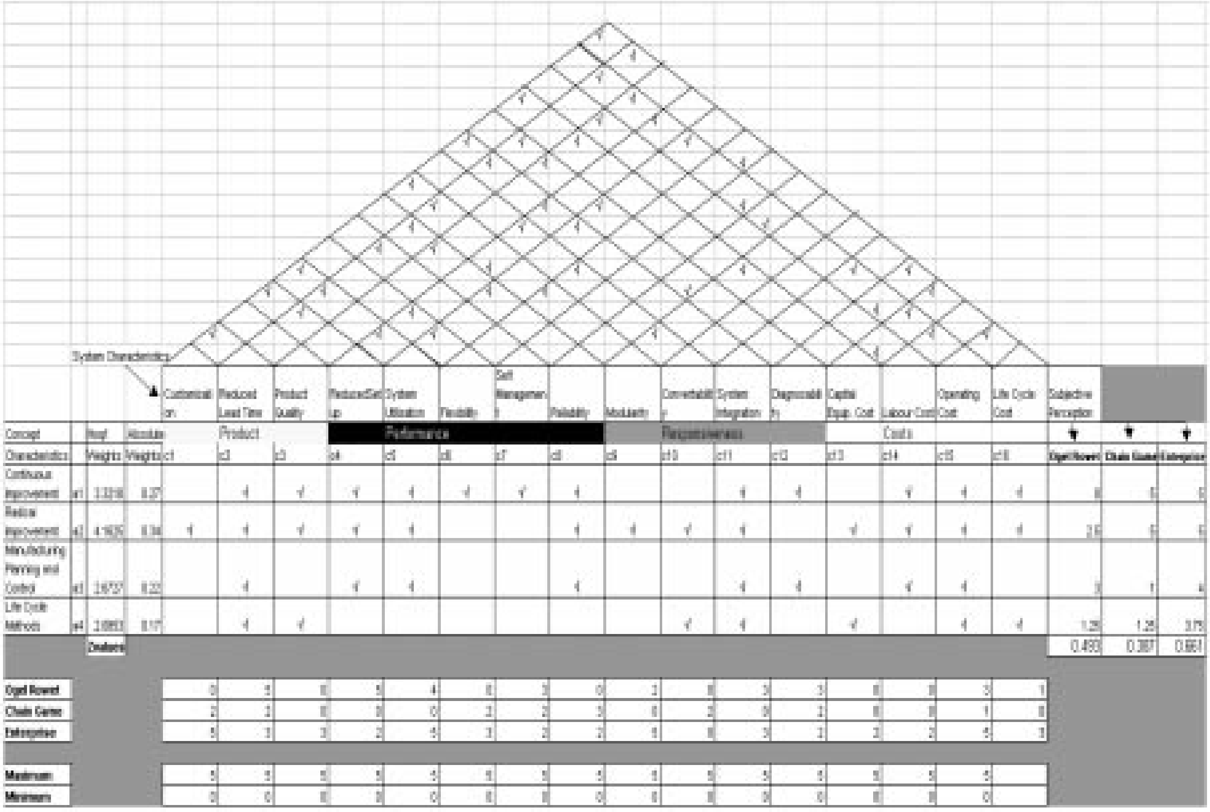

Fig. 7. The second House of Quality diagram.

Table 4. *Z* values for the games at the systems level

Game	Z Value
Ogel Rowet	0.493
Chain Game	0.387
The Enterprise Game	0.661
Target Game	0.612

minor alterations had to be made to the playing time in order to reduce the training session to one working day and hence the gaming time for the game for industry was reduced to 7.5 hours. In order to keep this design task restricted to one game for both industry and education, it was suggested that the game source code have a modular structure where modules could be removed from the game in order to reduce the number of problems that need to be addressed by the participants, thereby reducing the length of the training session.

SUMMARY OF THE DESIGN SPECIFICATIONS FOR THE NOVEL GAME

- Gaming media: computer-assisted role playing.
- Teamwork: two teams competing against each other.
- Concurrent engineering: medium level of concurrency in decision-making. In other words at least half the decisions should require various functions to co-operate in decision-making.
- Modular structure of the game program code.
- Concepts and issues to address: distributions in brackets (in descending order):
  - reduce product lead time (10.875%)
  - optimise operating costs (9.787%)
  - equipment and system utilisation (9.785%)
  - equipment modularity (7.621%)
  - reduce set-up time of equipment (7.621%)
  - customisation of products (7.613)%
  - self-management of production inputs (7.611%)
  - equipment diagnosability (maintenance issues) (7.591%)
  - equipment and system integration (6.518%)
  - equipment reliability (5.441%)
  - equipment and process flexibility (5.434%)
  - life cycle costs (4.347%)
  - product quality (3.255%)
  - capital equipment costs (2.173%)
  - equipment convertibility (2.173%)
  - labour costs (2.157%)
- Costs: medium level hence costs should be optimised as far as possible for a computer-assisted simulation game.
- Playing time: 9 hours for the educational game and 7.5 hours for the industrial version.

CONCLUSION

Figure 8 outlines the methodology employed by this project to achieve the objectives of ascertaining design parameters for a simulation game that illustrates issues that are likely to be faced by twenty-first-century manufacturing.

Quality functional deployment provided an efficient tool for translating the customers' voice into target engineering characteristics for a training game for next-generation manufacturing leaders. This paper successfully used subjective scales rather than engineering quantity scales for the 'Hows' in the House of Quality and obtained target-engineering characteristics for the new game. The summary of the result below gives a fairly satisfactory description of what students and corporate engineers feel are the design requirements of a next-generation manufacturing game. This was confirmed as only a few minor alterations had to be made at the validation stage. The results also reiterate the emphasis on faster product

Table 5. The computed target values of the system characteristics the novel game must illustrate, using linear programming, showing the calculated distribution and ranking of the system issues

System Characteristics	Variables	Computed Results	Relative Weights	Distribution in %.	Rankings
Customisation	x1	2.3334296	0.076125	7.613	6
Reduced Lead Time	x2	3.3334936	0.1087507	10.875	1
Product Quality	x3	0.9977019	0.0325487	3.255	13
ReducedSet up	x4	2.336094	0.0762119	7.621	5
System Utilisation	x5	2.9992797	0.0978474	9.785	3
Flexibility	x6	1.6658122	0.0543449	5.434	11
Self Management	x7	2.3330437	0.0761124	7.611	7
Reliability	x8	1.6678653	0.0544119	5.441	10
Modularity	x9	2.3361544	0.0762139	7.621	4
Convertability	x10	0.6648289	0.0216891	2.169	15
System Integration	x11	1.997994	0.0651819	6.518	9
Diagnosability	x12	2.3270013	0.0759153	7.591	8
Capital Equip. Cost	x13	0.6660372	0.0217286	2.173	14
Labour Cost	x14	0.6613142	0.0215745	2.157	16
Operating Cost	x15	3.0000153	0.0978714	9.787	2
Life Cycle Cost	x16	1.3325493	0.0434726	4.347	12

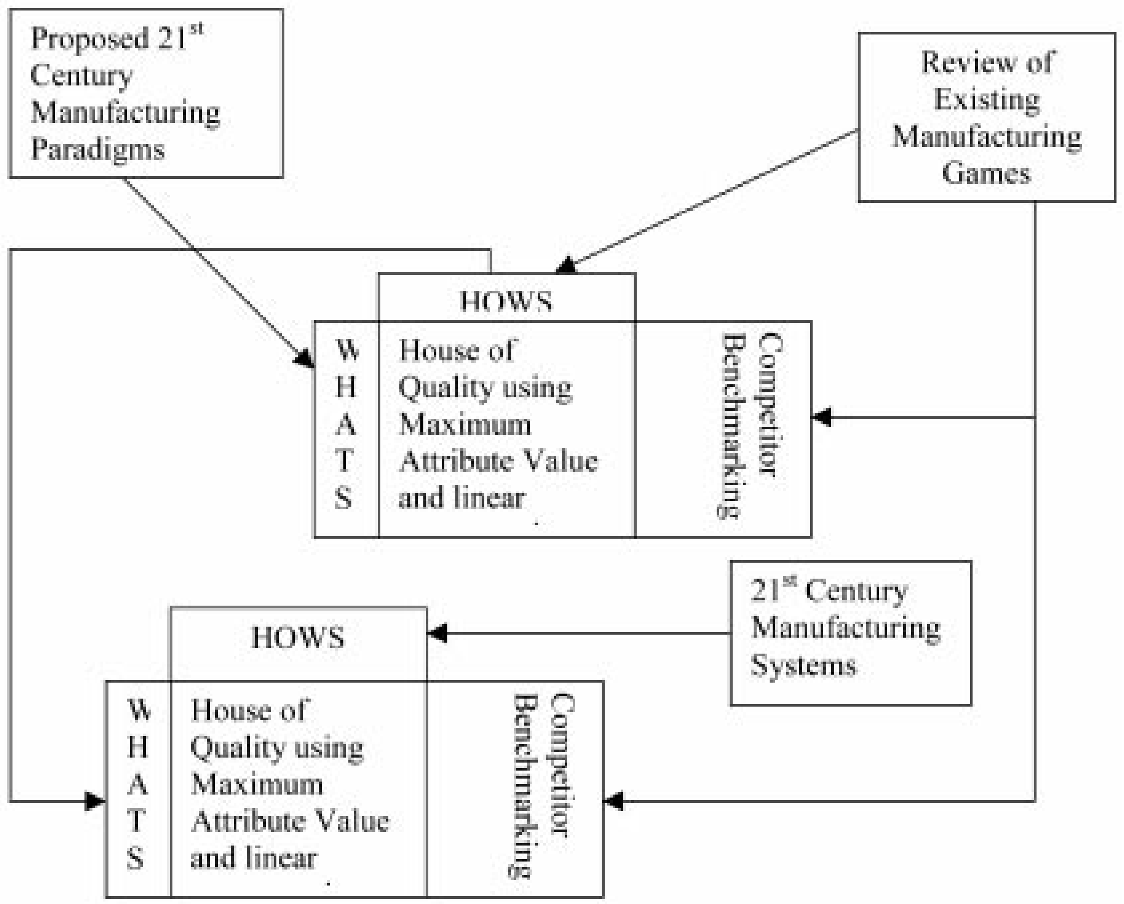

Fig. 8. The schema outlining the methodology of the paper.

innovation and flexibility and reliability of operations in next-generation manufacturing.

QFD can offer many benefits to the gaming industry by reducing lead times and by providing a better match of customer needs to game engineering characteristics, concepts and technology.

This paper also identifies the potential of exploiting the stealth learning effect of simulation games in the context of next-generation manufacturing. Simulation games can provide a laboratory of a dynamic real-world environment thereby facilitating experiential learning as well as in enhancing social skills and problem-solving skills. Moreover, while traditional methods of learning mean hard work for learners, games, on the other hand are enjoyed by their players for hours.

An area of improvement as is apparent from Tables 2 and 4 are the use of fuzzy linear programming techniques for the quality function deployment problems. In both tables the Enterprise game has scored the highest in terms of customer satisfaction, Z, rather than the target design. This is possible because, ‘optimisation uses as constraints the functional relationships assessed from benchmarking data set, which are not perfect’ [21]. Hence improved design values could be computed if this fuzziness in the data set was taken into account. Another method to improve the target design values is to study the effects of using a nonlinear multi-attribute value formulation. Perhaps this would be more suitable for the data set of the quality function deployment problems. This is an area that needs to be investigated in the future.

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