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Design histories for enhanced concurrent structural design

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ABSTRACT

The leisure boatbuilding industry has tight profit margins that demand that boats are created to a high quality but with low cost. This requirement means reduced design times combined with increased use of design for production can lead to large benefits. The evolutionary nature of the boatbuilding industry can lead to a large usage of previous vessels in new designs. With the increase in automated tools for concurrent engineering within structural design it is important that these tools can reuse this information while subsequently feeding this to designers. The ability to accurately gather this materials and parts data is also a key component to these tools. This paper therefore aims to develop an architecture made up of neural networks and databases to feed information effectively to the designers based on previous design experience.

I. INTRODUCTION

Leisure boatbuilding companies work within an industry that is highly competitive throughout the world. The markets are global due to the increased ease of transportation and the high capital markets to which the companies sell. Many companies are being developed in non-traditional boatbuilding countries and this is further increasing pressure on the industry. These factors mean that new potential markets must be quickly distinguished, scrutinized and acted upon to increase sales.

A key factor within the leisure boatbuilding industry are the aesthetics of the vessels. The boats must be of the highest quality as it is this factor that will attract customers and is, for many clients, the selling point of the vessel. Another key part to the aesthetics are the lines of the vessel. Each company has a very different appearance for their products and many companies require that new vessels look similar to the old vessels to create a brand. The appearance of the boats gradually changes over time to ensure that modern design trends are followed. This requirement often means, from a structural point of view, that the designs are very similar to each other creating an evolutionary rather than a revolutionary design environment. This means new vessels are designed by changing the dimensions of the old designs and determines that the new boats have similar layouts and parts to previous designs. This creates, within the industry, a large requirement for experience of the way in which design is carried out within the company. This knowledge of previous vessels can cut down on design times by reducing erroneous decision paths and can lead to better products by using the previous designs as prototypes. Currently many companies rely on “Design Gurus” who have been working at the company for a number of years to relay this information but this can be a problem if these members of the team leave.

This paper looks into ways in which evolutionary design can be integrated into design systems through automated methods. The aims of this type of design method are twofold. The method develops an input from previous vessels directly into the concept design stage to use successful products as a starting point for new designs. This idea develops previous work done in the development of genetic algorithms by developing and objective weighting method specific for boatbuilding [1], [2], [3] and [4]. Further to this a regular update to designers is given throughout the design process indicating what previous vessels have been created in the past and feedback information relevant to the new product. These methods therefore hope to increase concurrency, using automated communication, throughout the design process using feedback of previous comments made during the design stage thereby reducing design times so that old mistakes are not made again.

II. Literature Review

Concurrent engineering is a well established method for design which is successful in many industries as shown in tables I and II.

TABLE I
CONCURRENT ENGINEERING IN SHIPBUILDING [5]

Characteristic	Change
Development time	30-70%reduction
Engineering changes	65-90%reduction
Time to market	20-90%reduction
Overall quality	200-600%improvement
Productivity	20-110%improvement
Dollar sales	5-50%improvement
Return on assets	20-120%improvement

TABLE II
CONCURRENT ENGINEERING IN AEROSPACE [6]

Characteristic	Change
Development time	50% reduction
Engineering changes	50% reduction
Cost Savings	5% reduction

This success has led to increases in productivity by reducing the detailed design period therefore allowing more time for communication with other subsystems of design, e.g. structures, production etc., or a faster transfer to market. As the design can have an effect of 70-80% on the final cost [7] the ability to spend more time on design for manufacture can reduce the overall costs of the project substantially. This means that the design stage has an important part to play in the success or failure of a given product.

Concurrent engineering is not a new concept with many companies starting to use this technique from the late 1990's as reported in [8], [9], [10] and [11]. This means that lots of systems have been developed in the past. A definition widely used for concurrent engineering is "a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of cooperation, trust, and sharing in such a manner that decision making proceeds with large intervals of parallel working by all life-cycle perspectives early in the process, synchronized by comparatively brief exchanges to produce consensus." [12]. The emphasis of the definition is upon brief exchanges to produce the consensus and this can best be done through an automated approach. The increased ability to use computational methods to share information and data is therefore the next step forward with increased data management and optimisation programs helping designers to understand the problems faced by other subsystems.

A number of key points that are brought up within concurrent engineering are:

- Parallel design
- Multidisciplinary team
- Facility
- Software infrastructure
- Support and understanding for the environment

Further to these techniques other tools often fall under the umbrella of concurrent engineering [6]:

- Integrated Project Teams (IPT)
- Digital Product Definition (DPD)
- Digital Pre-assembly/Mock-up (DPA)
- Computer Integrated Manufacturing (CIM)
- Lean Manufacturing (LM)
- Design for X-ability (DFX)
- Total Quality Management (TQM)
- Quality Function Deployment (QFD)
- Supplier Involvement on Product Team (SI)
- Customer Involvement on Product Team (CI)

The aim of this work is to develop a part of the software infrastructure to help understand the of the members of the multidisciplinary team by creating tools that aim to include QFD, DFX, CI and TQM.

An advancement to the development of concurrent engineering for will be the development of automated feedback to designers from different subsystems of design. This will reduce the need for time expensive communication as designers can change their design patterns based on this feedback from design tools. This work has already been started using multiobjective optimisation such as through genetic algorithms [2], [3] and [4]. To make this form of optimisation a more useful tool for industry, either pareto sets have been developed to help select the correct dimensions or, in order to make these algorithms more objective, the use of Quality Function Deployment has been employed [13], [1]. The development of an objective input method using past design histories has therefore been developed using neural networks to give inputs from the past. Further development of automated feedback to designers has also been included using design histories to reduce the communication required between different subsystems.

Boatbuilding is not well published within literature, with much information being taken from shipbuilding and aerospace due to the similar trends in production. The boatbuilding market is split between many different boat dimensions and within these categories also exist different types, styles and qualities of boat. From fig. 1 it is possible to see that within the British boatbuilding market a comparison of Fairline, Sealine, Princess and Sunseeker shows that most of the companies have a distinct area that they sell to. Even though there is overlap, these companies do not always have a large competition between them.

Development of a brand throughout a company means that the products produced will have a similar look to each other. This means that despite size differences in a brand, superficially the designs are very similar. This indicates an evolutionary design process where each design is built upon from the last rather than a revolutionary design process. This is especially true in structural design where the hull lines are similar from boat to boat and therefore a very similar structural problem must be solved for each new vessel. Low profit margins ranging from 3%-10% [14] for UK companies lead to the industry being unable to afford expensive training costs and cannot afford to have engineers slowed down by learning new tools. Further to this a low materials efficiency index reported in [14] for 3 of the major UK companies indicates that these companies are either paying too much for the materials being used or are inefficient in their use. While structural design may only be a low percentage of the overall mass, 10-15%, this is mass that is not used for marketing of the vessel and therefore is an area where weight savings add a large benefit. Further to this the structural design of the boat is where material efficiency could also be improved through helping production engineers to design easy to produce boats. The use of using previous designs and reducing the previous mistakes made could be an area to reduce the design times and could be carried out using neural networks.

Neural networks are used throughout many different applications due to their great strength in being able to automatically “recognise” the differences in pictures and data. Neural networks also have a great ability to learn over the time that they are used. This means that design systems can constantly be updated as companies and designers help to evolve the tools with use. Neural networks are based on the function of neurons in the brain and were originally looked at by McCulloch and Pitts in the early 1940’s [15]. It was not until the 1960’s when the ability to develop learning algorithms was created by Rosenblatt [16]. This was further developed into the 1970’s and 1980’s where back-propagation was independently developed by a number of authors Werbos [17], Rumelhart, Hinton and Williams [18], [19] and by Parker [20]. This new technique allowed neural networks to be more capable at solving more complex problems. In recent years there has been further evolution of neural networks allowing an integration into many different industries. This can then be further developed as an aid to concurrent engineering by giving feedback from past designs which will then take the place of some of the direct communication between subsystem engineers. The use of evolutionary tools as an automated concurrent information transfer system should help to further reduce these time cycles by removing the transfer of knowledge during communication

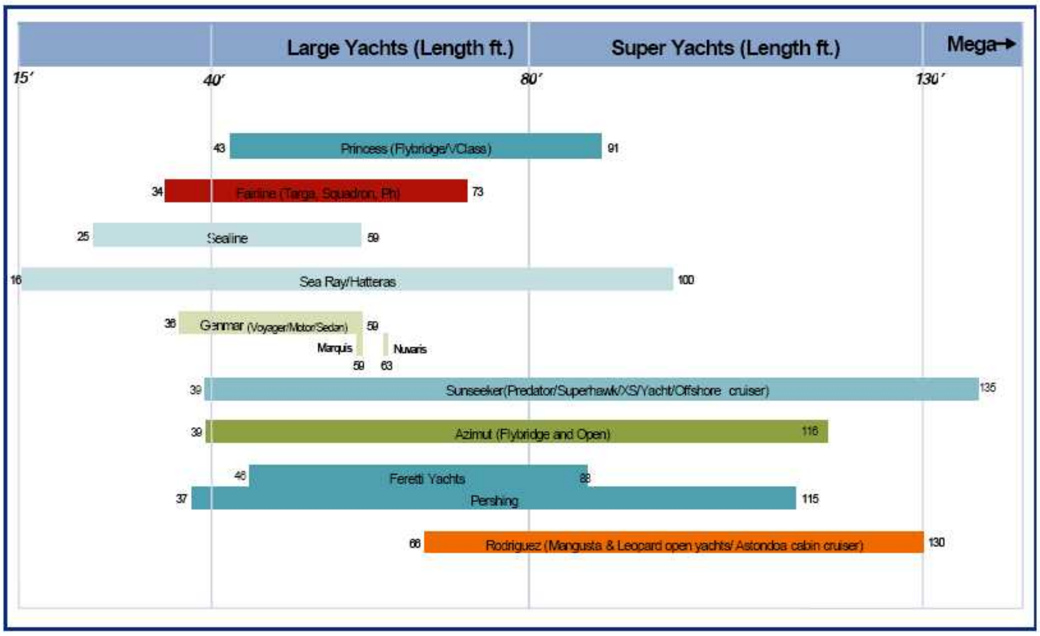

Fig. 1. Boat sizes produced by boatbuilding firms [14]

to focus on innovation.

III. Methodology

A. Design Method

The method for the design will follow a standard route from the initial stages of concept design through to an iterative detailed design process that for effective design should also involve the production engineers as shown in fig.2.

From fig.2 it is possible to see that the philosophy has been based on the structural design process and involves a number of different inputs. These different areas of interest will be partly inputs from other design subsystems while others will be key areas that are important to develop a successful structural design. Further the production engineers' expertise must be included to make sure that the design is as low cost as possible to produce.

The design starts with the beginnings of a concept where a customer/objective puts forward an idea for a new vessel. It is then important to gather some thoughts about what will be important to this new customer so as to create the best possible design. Using an idea called Quality Function Deployment, a technique that has been popular in industry since the late 1980's [21], it is then possible to quantify these ideas and relate them to design criteria or quantifiable information about the boat. From here a rough idea of how the boat will look can be created and ideas can start to be formed into how this problem can be solved. This should be done using past experience, either through similar designs or with the knowledge that old designs will not be able to handle this new objective. From here an idea can then be brought forward into the main design process.

The detailed design will be an iterative design process adding further detail to the concept that has been created. This process uses all of the subsystem designers working together to come to a final solution for the vessel. This process should involve all of the design team to reduce lengthy redesigns and to lower the final cost. Each subsystem engineer will work more closely with some members of the design team and have more of an influence on their work. Much time can be spent during this phase discussing compromises in design between the different subsystems. It is

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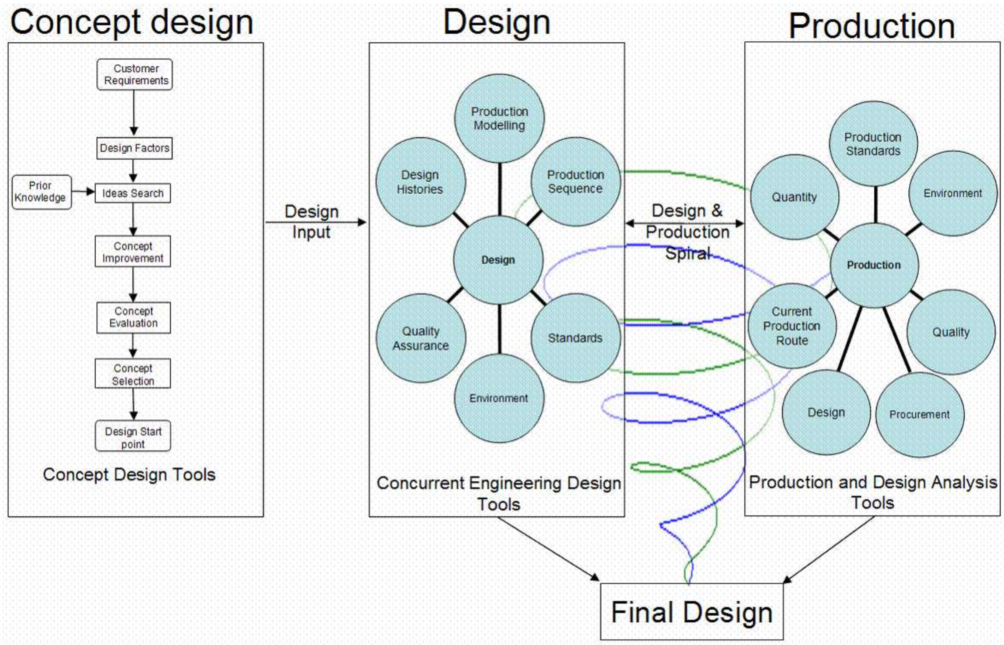

Fig. 2. Structural Design Spiral

therefore important that these relationships are discovered to encourage further compromises and an understanding of subsystems that an engineer will work closely with. Further to this it is also likely that subsystems, other than structural, will have different areas of importance effecting them as represented by the bubbles in fig.2. Finally the boat will be produced and sold. At this point feedback must be gathered so that future designs can use the successes from this design while building on the problems encountered.

Within this design framework it can be seen that there is a requirement for feedback from design histories within the detailed design section and this will be fulfilled by the use of automated searching of previous version histories of the designs developed using neural networks. The concept design section also requires input from previous designs that have a similar potential size or task and this tool can implement this process for successful past designs. This work will encourage concurrency within a design by giving each subsystem experience of the problems faced by the other subsystem engineers they work closely with. Each stage will require different tools as detailed design, by its own nature, will require more data than in the early concept which only requires a flavour of the successes and failures of previous products.

B. Concurrent engineering environment

The concurrent engineering environment has been established to suit the needs of the industry while being low cost to implement. The main tool will be the data exchange required for the effective communication of subsystem engineers. It is through this sequence that data can be automatically be transferred, permeating the changes throughout the design phase.

The system works by using spreadsheets as the main data storage system. Many designers use this format to carry out calculations already and it also requires little programming knowledge to make changes to the system. From these spreadsheets it is very easy to transfer data from other software including CAD systems or in-house tools. During the design phases work can be carried out, and in design breaks, while further work is discussed, the spreadsheets can be updated and the current version automatically saved.

For the architecture of the system, each of the subsystems will have their own spreadsheet. On this there is room for calculations to be made but also worksheets for the transfer of the data. The system works by requests of data which can be seen in fig. 3. When a designer, as an example the layout engineer, requires a piece of data, the distance between stiffeners, they send a request to another subsystem, the structural engineer, for the data they require. This request will then be transferred throughout the system through the data exchange, controlled by the team leader who can see all of the information being transferred and keep an eye on data that is required but unavailable, and to the subsystem the data was requested from, the structural engineer. The request can then be replied to, by the structural engineer, with the data required, the stiffener spacing. By linking this information the data can then be passed between the spreadsheets. Once the data is linked, all of the changes made will then be passed between the subsystems at each design break in this example it may mean that a room is automatically reduced in size by the structural engineer changing the stiffener spacing. This also means that the team leader has all of the information that is available and can keep track of the ways in which the data effects other data throughout each iteration. They can also keep track of key data that may be holding up many subsystems and therefore needs to be determined at an early stage.

Further to this any data will be passed to the "parameters store" leaving only one database to be searched through by the neural networks. This parameter store has all of the different component parts of this version of the design, all linked to the initial subsystem from which they came from. Once all of these connections have been made it is then possible for the parameter store to be automatically updated giving the characteristics of the vessel in one place. It is also possible to connect different pieces of software to the subsystem spreadsheets so that work produced outside of the system will automatically update the other subsystems: designers are then not inhibited by the workings of the system.

IV. Design History Tool

A. Neural Networks

The neural networks within the system will be used to search through the different databases that are available in order to disseminate information to the designers as to possible other techniques, parts and materials that are available within the current markets and previous designs that are used. This ability to search through these designs will help engineers to explore new possible design routes and will also help the production engineers to give feedback on the suppliers that are most reliable. As the design is carried out the neural networks will catagorise new parts and lines that are being drawn. As the new parts are drawn they will be able to determine what this data indicates as a likely part or previous design that is already in the database. The weightings from the neural networks will be "taught" by all members of the design team. This will be done by gaining feedback from the presented parts against the parts that are accepted by the designer. The parts will be listed in order from best to worst taking into account all of the engineers associated with the project. Connected to this data will also be information from other subsystems further allowing the designer to take a holistic view of a certain part.

Neural networks are based upon the theory of neurons in the brain to develop "adaptive learning". Neurons in the brain work by being stimulated by an electrical pulse. Further pulses can then be sent forwards to more neurons and, depending on the neurons stimulated, memories can either be remembered or created. The basic formula for the stimulation of each neuron is therefore shown in eq. 1

$$\begin{array}{l} f_j(\sum w_j x_j) \geq i \;\; f[j+1] \rightarrow 1 \\ f_j(\sum w_j x_j) < i \;\; f[j+1] \rightarrow 0 \end{array} \tag{1}$$

where f_j= non-linear function w_j = weighting function x_j= input from previous node and i=node threshold. From these equations it is possible to see that the neurons take impulses from neurons connected to them and give certain outputs based on the stimulus. Eventually an output will be

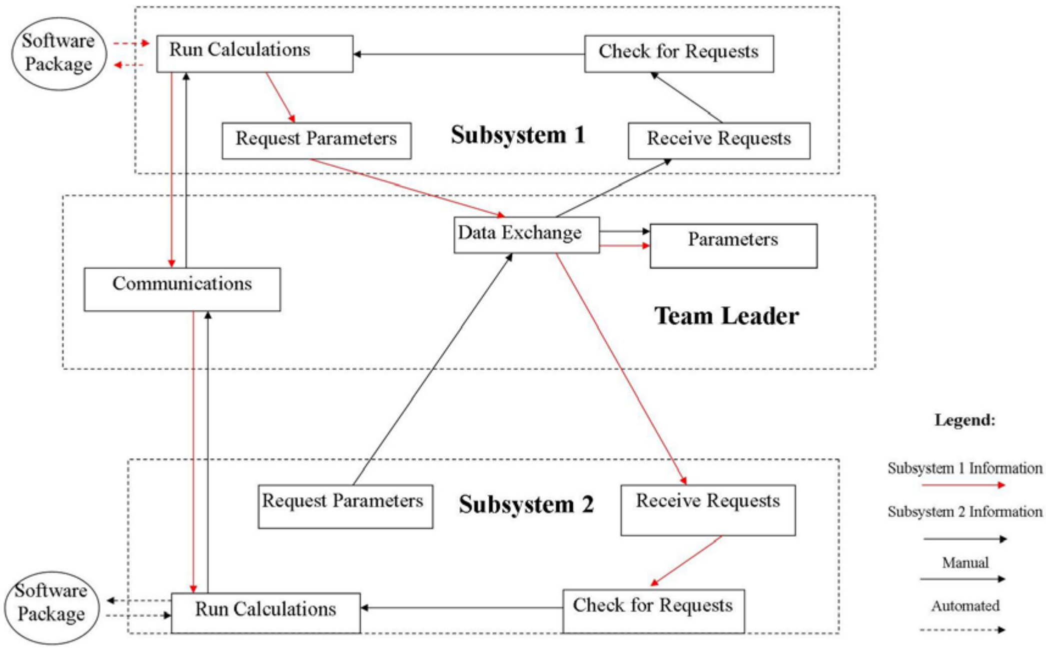

Fig. 3. Concurrent data transfer method

chosen which most closely emulates the inputs that have been given.

There are different sorts of networks that react in different ways so that the characteristics of learning that are required can be given. The recognition of different parts can be a relatively easy task as the pre-grouping of different types of part can easily be carried out, such as engines or turbines. This gives a relatively simple problem with few parameters outlining a different engine. The recognition of different lines plans within a CAD drawing could be a more difficult task due to the multitude of different parameters that will go into it and will therefore involve the use of multi-layer neural networks. To make sure that all parts can be determined using the same system a multi-layer neural network system has therefore been employed.

The basis behind a multilayer neural network is that there are input and output layers which in between have a number of hidden layers. If the activation function for the hidden units is $g(u) = 1/(1+e^{-u})$ and for the output units of $g(u) = u$ and the network has been set up to determine the functions $y_i = F_i x_k$ from the input variable x_k to the output variable y_i the number of layers can be determined using eq.2

$$y_i = \sum_j w_j x_j - i \tag{2}$$

for no hidden layers and for one hidden layer eq.3 can be used

$$y_i = \sum_k W_k g\left(\sum_j w_j x_j - i\right) - \theta_j \tag{3}$$

According to Cybenko [22] for an arbitrary accuracy, no more than two hidden layers are required (assuming that there are enough given units per layer), but that only one layer is required for continuous functions [22], [23]. Since the variables that will be entered into the neural network will be continuous the networks have been produced with one hidden layer as can be seen from fig.4.

The final step in the determination of the neural networks will be to find the method of learning for the network. The network will need to be a continuously learning network so that all of the feedback gathered over time will aid the system. For the system to be immediately useful there

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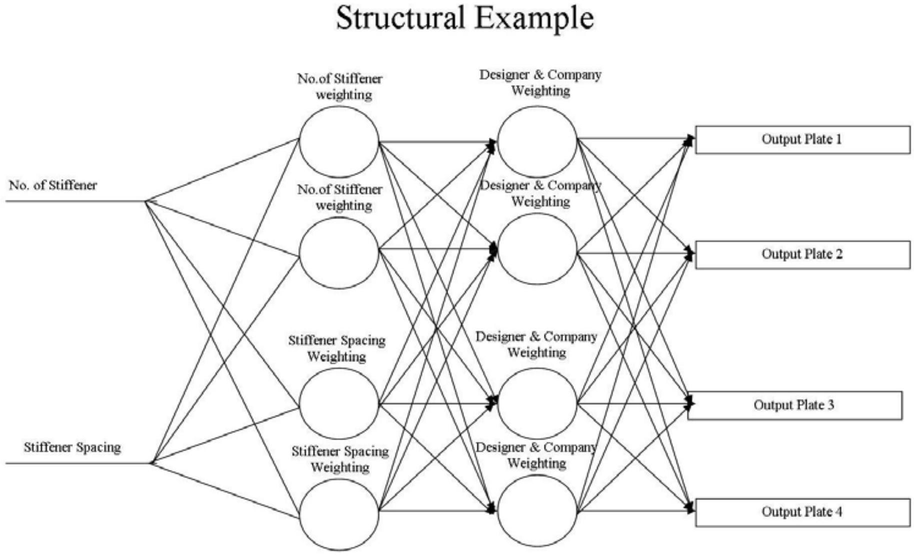

Fig. 4. Neural network engine example

is a requirement that the networks have already learnt to recognise bits of the system. The system will need an initial training period followed by a continuous period of learning while the software is working. The designers themselves have an opportunity to give feedback to the system but this may not always be forthcoming. This therefore determines that the system should have a capability to deal with both supervised and unsupervised learning.

The ability of the neural networks to learn means that increased numbers of designs educate the neural network tool, providing increasingly helpful solutions. The design will be able to take learning from individual designers using the tool, companies they work for, vessels similar in type and also the entire industry as a whole if database information is shared. This should allow an increase in innovative new designs and the increased capability to learn from past successes and mistakes.

B. Databases

To receive the full benefits from the system databases of information will need to be constantly updated with up-to-date information and feedback will need to be developed, about previous designs, for the use of the system. The databases will be in three main parts:

- Materials database - Consisting of fibre and resin types etc. rated on materials properties and supplier ratings
- Parts database - Consisting of different boat parts, e.g. engines, rudders and turbine blades, that will be rated on mechanical properties, dimensions and supplier ratings.
- Design history database - Previous design versions will be saved and new designs will be compared on an overall basis and a subsystem by subsystem basis to try and create matches. The designs will be rated on similarity to previous vessels and success of those vessels.

Due to the nature of boatbuilding even though companies may work in a similar area they often do not directly compete with each other on like for like vessels. This means that these companies can start to share resources together. Through the use of grid computing it is possible to collate information between the different companies within the industry without the insecurities of directly transferring this data. This requirement means that even though the companies may be small, as an industry they have more of an ability over the supply chains by switching from companies that regularly give poor service. It also means that a company developing a new boat may find a competitor already failed or had a large success in that area steering them to follow other objectives.

Each of the different databases will have to work in slightly different ways depending on the inputs that are given to them. The materials database can have data entered into it in any manner that is required as this data will come from independent research companies compiling the database. The parts database will be input using a web service that will allow outside companies to enter the required data for their component, this information can then be fed to an XML relational database to allow for easy searching. Finally the design history database will be created using spreadsheets as this is the method used for the designers to transfer their data throughout the system. This system will also allow the creation of a relational database of the version through the use of standard name types and subsystem headers. The only difference with this database will be the problems that could occur between different designers calling different dimensions by different names. This could therefore rely on a standard set of names that are to be used throughout the company for each different dimension. The reuse of old spreadsheets would also allow this to occur very easily as all names would be entered and only numbers would need to be changed or adapted.

Each of these different databases will be affected by different subsystems. The search time for each of the tools can be cut down upon by removing the requirement to investigate certain databases during this period. This means that if certain dimensions have been picked up for an engine then the propulsion subsystem will be the database which is compared against. This will help to reduce computational expense and to reduce the busy computational period between design sessions.

V. Design Methods

Structural design is increasingly using optimisation to increase the quality of the design while also reducing the time to complete production. Optimisation can be carried out with many different techniques though currently, for use within structural design, the most common technique is that of the Genetic Algorithm (GA) as used by Okada et al. [24], Nobukawa et al. [25], Sekulski et al. [26], [27], [28] and Maneepan et al. [29]. This technique is often used for multiobjective optimisation as its stochastic nature allows a thorough investigation of large search spaces without getting stuck at local optima. This sort of optimisation therefore allows a level of concurrent design between the structural subsystem and the production engineers. The drawback in the use of automated systems is that they rely on an objective function to determine which of the results is the best for the problem to be solved.

Genetic algorithms work by copying the process of DNA transfer in living organisms. They then use the process of evolution to find the optimum solution for a given search space. The search space is populated by a number of strings representing the topology of a structure. These strings can then be used to determine the properties of the structure through modelling as shown in fig.5.

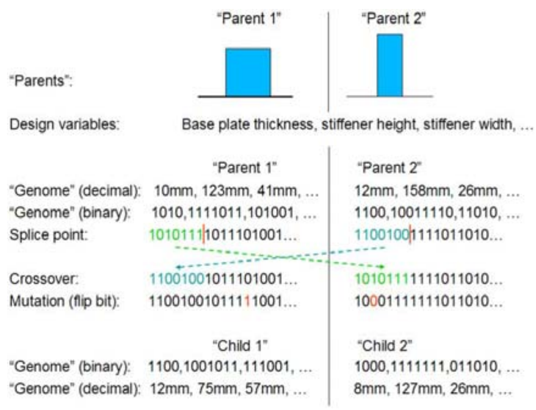

Fig. 5. Genetic algorithm used for a tophat stiffened optimisation

Having completed this modelling an objective function can be determined using eq. 4,

$$W = \sum_{n=1}^{N} p_n w_n X_n, \qquad (4)$$

where p_n=importance of the variable, w_n=weighting of the variable, X_n=variable output. The *variable output* is the value of the output that requires optimisation, the *weighting* of the variable is required to make sure that values are approximate to each other in size so as to make sure that one of the objectives does not become dominant in the optimisation. Finally the *importance variable* will determine how key this output is to the end of the design. This is normally done subjectively by a designer who will select in what order they feel the outputs should be made in. This can lead to problems as this may not fit in with the customer requirements, leading to a faulty optimisation.

The aim of Quality Function Deployment is to objectively determine the important parts of a design during the concept design phase. This technique has been developed to allow the inputs of the customer requirements to be quantified and compared with the design criteria. This will then allow the designer to determine rough guidelines for the dimensions of the product. This technique also develops quantifiable data into which of the customer requirements are the most important and therefore which design criteria are the most important. This data can then be used as the weightings for the genetic algorithm ensuring that the optimisation follows the customer requirements. This will lead to designs that are customer/objective specific.

For each of the QFD runs that occurs each of the different inputs should be kept. The different possible outputs for the optimisation can be listed as specific outputs. This means that when a certain combination of inputs are put into the boat then certain weightings are presented to the genetic algorithm as can be seen in fig.6. As designs are completed and sales occur it will be possible to negatively load the weightings that create unsuccessful designs and encourage future designs to use the weightings used in successful designs.

As has been shown, the boatbuilding industry is one where evolutionary design is very important. This therefore indicates that designs that have been successful in the past can be a major factor in helping new designs stay successful. It is therefore important that the optimisation routines involve a level of previous design importance. This tool aims to develop the well used technique of Genetic Algorithms for a more industry specific application through the introduction of QFD and through further developing this tool to work within the evolutionary nature of boatbuilding.

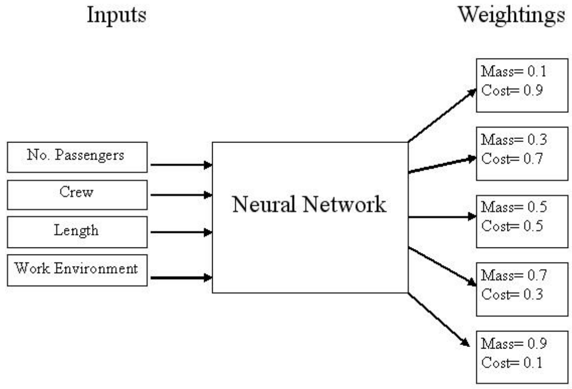

Fig. 6. Example of inputs and outputs for Genetic Algorithm

VI. Conclusion

This paper has outlined the requirements for previous design histories to be taken into account throughout an evolutionary design process. Through this requirement a system has been introduced which can investigate previous and new structures. The ability of this system to learn as new designs are created allows it to evolve. This gives the designers more relevant information based upon the way in which previous designs have been carried out. New potential information can then be streamed while allowing designers an ability to look through previous designs. This increases feedback from previous designs allowing concurrency to be developed though the previous design histories that have been used. This will allow decreases in design times as the requirement to communicate using DFX techniques will be reduced.

The paper also determines an objective method for the determination of weightings for genetic algorithms specific for the boatbuilding industry. The work done improves previous work to design an objective method by taking into account the evolutionary nature of the boatbuilding industry. The need for an objective method of weighting determination will be important to remove the designers subjective opinions until the iterative stages of design where human critical analysis and creativity can improve on the initial designs created through optimisation. This will allow optimisation to become a more powerful design tool within the boatbuilding industry.

The method is part of a larger concurrent engineering system which gives the capability of feedback from previous designs the potential to permeate through new designs. This will encourage design for production through the modifying of past mistakes. This method will also allow production engineers more control over the supply chain through negative and positive feedback and increases the knowledge of structural designers in the area of material design. The inclusion of a number of databases will help to increase innovation and will also allow the safe transfer of information between boatbuilding companies within conglomerates.

In the future key areas to be developed will be:

- Teaching of networks to recognise structures.
- Investigation of weight changes to allow the correct realignment as designers make decisions.
- Case study testing of the structural optimisation with design history attachment.
- Determination of optimum database sorting networks to effectively search designs.

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