THE USE OF A FUZZY LOGIC SET-BASED DESIGN TOOL TO EVALUATE VARYING COMPLEXITIES OF LATE-STAGE DESIGN CHANGES

(DOI No: 10.3940/rina.ijme.2012.a4.241)

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SUMMARY

Advanced design methods, such as set-based design (SBD), can provide a structured approach to evaluating the design space in order to make accurate and informed decisions towards reaching a globally optimal design. The set-based communications required to appropriately implement SBD are counter-intuitive to the point-based communications of a typical design process. The use of a hybrid agent fuzzy logic design tool can help to facilitate the SBD process by ensuring the use of set-based communication of design variables. The design tool uses automation of certain aspects such as data collection and analysis while still allowing for input from human designers. One important advantage of using SBD is the ability to delay decisions until later in the design process when more information is known. This paper focuses on the robustness of the SBD process and its ability to handle late-stage design changes of varying complexity. Multiple SBD experiments instituting design changes of varying magnitude late in the design process were conducted using a hybrid agent fuzzy logic SBD tool. A simplified planing craft design was utilized for the experiments. Conclusions regarding the robustness of the SBD process under late-stage design changes were determined and outlined using information gathered by the SBD tool.

NOMENCLATURE

HAFL	Hybrid Agent Fuzzy Logic
SBD	Set-Based Design
SOC	Special Operations Craft
L	Length
B	Beam
β	Deadrise
LCG	Longitudinal Center of Gravity
Δ	Full Load Displacement
VCG	Vertical Center of Gravity
τ	Trim
λ_w	Average Wetted Length-to-Beam Ratio
Fn_B	Beam Froude Number
ABS	American Bureau of Shipping
P	Preferred
M	Marginal
U	Unpreferred
T1-FL	Type-1 Fuzzy Logic
MF	Membership Function
JOP	Joint Output Preference
T1-FLS	Type-1 Fuzzy Logic System

1. INTRODUCTION

While ship design remains a highly intensive and complex process, advanced design methods such as set-based design (SBD) can provide a structured approach to evaluating the design space while moving towards a globally optimal design. SBD has been used for applications in the automotive and aerospace industries, but has recently been proposed for the ship design process [1]. Proper implementation of the SBD process "requires shifting to a paradigm where design team members reason and communicate about sets of designs" [2]. In reference to the SBD process, Ward et al states, "Since there is no proven formal methodology, learning the process will be slow and error-prone" [3]. The development of a design tool can help provide a more formal methodology for the SBD process.

A hybrid agent fuzzy logic (HAFL) design tool was developed at the University of Michigan to simplify communications of design variables and solutions within the SBD environment by automating aspects such as data collection and analysis while allowing for human designer input [2]. One important advantage of using SBD is the ability to delay decisions until later in the design process when more information is known and design tradeoffs are more fully understood [3,4,5]. In an effort to confirm the theoretical advantages of SBD, the HAFL design tool was used to facilitate a ship design case study using the SBD process. Specifically, this initial study focused on the evaluation of how delaying design decisions using SBD could cause higher adaptability to varying complexities of design changes later in the process.

Multiple SBD experiments instituting design changes of varying magnitude late in the design process were conducted using the HAFL SBD tool. Human designers were used to provide preferences on design variables from different design perspectives. By documenting how the SBD process handles changes in designer preferences, the impact of design requirement changes can be determined.

A simplified planing craft design was selected for the design experiments. The representative mission for the planing craft design was based on the Mark V Special Operations Craft (SOC). The ship design was broken down into independent functional design groups (to be defined in Section 3) and the groups are represented as design agents in the HAFL design tool. The design groups utilized mainly empirical calculation methods for their design analyses. The research outlined in this paper focuses on the HAFL design tool and the SBD process, not the complete and proper evaluation of the Mark V mission profiles or all aspects of a planing craft design. Therefore, there are certain assumptions made in order to not detract from the main focus of the research. These assumptions are discussed throughout the paper.

2. SET-BASED DESIGN

SBD is design by elimination of infeasible or dominated solutions. The SBD process can be described as a concurrent engineering approach with the following characteristics:

1. Considers a large number of design alternatives through an extensive exploration of the design space,
2. Separate groups of specialists are able to evaluate the design and provide preferences for solutions based on their own perspectives,
3. Intersections between sets are used to establish feasibility before commitment and guide the design towards a more optimal solution, and
4. Fidelity of analysis is increased as the design progresses [6,7].

Figure 1 provides a visual depiction of the SBD process. The different circles represent the set-ranges of different functional design groups. By exploring the design space, intersections between groups can be identified. The highlighted portions show these intersections. As the design progresses downwards in the figure, the sets continue to be narrowed through the elimination of infeasible or dominated solutions.

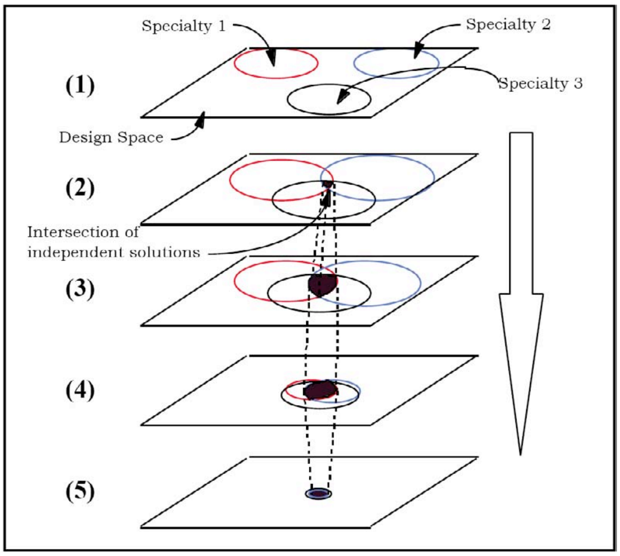

Figure 1: Set-Based Design Process [6]

SBD allows engineers to evaluate tradeoffs of a design with conflicting goals by gaining more information before making decisions. During the intersection phase of the design process, each functional group has an opportunity to influence the first set of design variables, which leads to a large set of possible solutions [8]. Decisions are made to eliminate parts of the design space when trade-off information is better known or eliminated by dominating solutions. At a point when all sets are feasible and all tradeoffs are explored, the best possible design can be selected.

In early stage design, decisions are made that commit costs and affect performance in the final product. These decisions are made when the least amount of information is known about the design. To delay decision-making, SBD uses ranges to define design variables so the design can continue until an informed decision can be made to limit the design space [7]. This prevents decisions from being made too early based on a small amount of information. Only when sufficient knowledge of the design is known are options eliminated. By keeping the variables open longer, the amount of rework required is mitigated if a change is made to the design requirements. The SBD process of delaying decisions helps foster the attitude of making the right decision the first time.

3. EXPERIMENT PREPARATION

After selecting a planing craft design for the experiment, a basic mission profile and requirements needed to be developed. Also, planing craft functional design groups and variables were selected. Finally, a computational design tool was developed for each functional group.

3.1 REPRESENTATIVE MISSION

The basic mission profile and general requirements for the planing craft design were based on the Mark V SOC. The Mark V is mainly used to carry Special Operation Forces such as Navy SEALS into and out of operations. Secondary missions include coastal patrol and interruption of enemy activities. A typical detachment consists of two Mark V crafts that can be transported by two C-5 aircraft or launched from a well or flight deck [9]. The general characteristics of the Mark V were used to verify the design tools developed and helped generate the initial ranges for the variables. The basic design requirements adapted from the Mark V mission profile included speed, range, payload, and sea state [10].

3.2 FUNCTIONAL DESIGN GROUPS

The initial stages of the SBD process require the determination of what functional design groups (i.e. weights, stability, etc.) are to be considered for the planing craft design. The functional groups for these experiments were selected based on general components of most planing craft. The selected functional groups include:

- Resistance,
- Weights,
- Dynamic Stability, and
- Seakeeping.

For the purposes of the experiments discussed in this paper, these four functional groups, also known as design agents, provide enough information about the craft to simulate a set-based preliminary design. For more detailed analysis, additional functional groups could be added including areas such as propulsion, arrangements, or structures.

Each functional design group has an objective that they hope to optimize. The objectives for each functional design group include:

- Resistance: minimize the resistance of the hull
- Weights: minimize a weight criteria value that ensures displacement is greater than the weight estimate
- Dynamic Stability: minimize trim to reduce porpoising effects
- Seakeeping: minimize vertical accelerations for the given sea state requirement

Details on each functional group, the principles used, and constraints are discussed in later sections of this paper.

3.3 VARIABLES AND REQUIREMENTS

Variables and parameters were selected for the planing craft design based on their influence on the design itself, and whether or not they were required by the agents. Using the four design agents, variables were selected based on the possibility of conflicting preferences between two or more agents. A preference can be defined as the design variable values that are more preferred than others by an agent. For a SBD, negotiated design variables usually include the principal dimensions of the craft because most agents have preferences for these values. The number of variables was limited to those needed by the mainly empirical methods used by the design agents and with the purpose of simplifying the experiments. The selected design variables were length (L), beam (B), deadrise (β), longitudinal center of gravity (LCG), and full load displacement (Δ). The five variables were chosen to represent the values with the most significant impact on the planing craft design.

Negotiation of a design variable is only required when functional agents prefer different values. For displacement, higher values increase resistance while lowering vertical accelerations. A higher deadrise increases resistance but decreases vertical accelerations. For the longitudinal center of gravity, an LCG further from the stern increases resistance while reducing trim. These trade-offs dictate the negotiation of these design values.

There are also design requirements based on the representative mission that are provided to the design agents. These requirements include speed, range, payload, and a representative wave height associated with a sea state. While ranges of design requirements would normally be used in a full SBD, this experiment used single, discrete, requirement values. A single value was chosen because the SBD process was being utilized to determine the potential design space for a planing craft preliminary design, as opposed to searching for a single feasible solution. Also, the goal of the experiment was to test the robustness of the SBD process, not the value of SBD. The benefits of SBD are discussed in [2], [3], [5], [6], and [8]. The negotiated variables and design requirements can be seen in Table 1.

Table 1: List of Negotiated Variables, Requirements, and Interactions

	Unit	Resistance	Seakeeping	Stability	Weight
Variables					
Length (L)	ft	N	N		N
Beam (B)	ft	N	N	N	N
Deadrise (β)	deg.	N	N	N	N
Long. Center of Gravity (LCG)	ft from stern	N		N	
Full Load Displacement (Δ)	lbs	N	N	N	N
Requirements					
Speed (V_k)	kts	In	In	In	In
Range	nm				In
Payload	lbs				In
Significant Wave Height ($h_{1/3}$)	ft		In		
		In = Input		N = Negotiated	

3.4 TOOL DEVELOPMENT

Each design agent needs a tool to complete the objective of their functional component of the design. These tools could range from a simple spreadsheet to sophisticated software. A large part of the preparation for the experiment included determining what tools should be used for each design specialty. All tools were developed based on accepted methods from the planing craft field. Some tools used first principles while others were empirically based equations. Also, a design methodology was developed to guide the design agent in charge of using the tool. In an attempt to make the experiments run as smoothly as possible, substantial effort was put into making sure the agent evaluation process was as clear and user-friendly as possible. The tools developed automated the design space exploration to ensure that a large sample of combinations of variable values was evaluated. Each subsection will discuss the tool in more detail and provide the references used.

After defining the tools used by the design agents, the inputs can be identified to form a better idea of how the variables and requirements interact between agents. Selecting the agents' tools also dictate certain inputs that are required. Table 1 provides the interactions between the variables and requirements with the agents. Table 1 also gives an overview of the inputs and outputs of each agent and a look at what variables and requirements are important to the agents.

3.4 (a) Resistance Tool

The objective of the Resistance agent is to minimize resistance of the planing craft. Savitsky's method was used to estimate the calm-water resistance of the planing craft design for this research [11]. Using additional resources on Savitsky's method, a MATLAB program was modified for the Resistance agent to use during the experiments [12]. Due to the small impact on the estimated resistance, values for the vertical center of gravity (VCG) and shaft angle were assumed and held constant. Constraints on the objective function were related to the limitations of the method used. These constraints included restrictions on trim (τ), average wetted length-to-beam ratio (λ_w), and beam Froude number (Fn_B).

3.4 (b) Seakeeping Tool

The objective of the Seakeeping agent is to minimize vertical accelerations. The wave impact accelerations were estimated using a method described by Savitsky [13]. There are certain limitations to this method as well, including a restriction on the acceptable length-to-beam ratio. Also, American Bureau of Shipping (ABS) Guidelines on vertical accelerations for a planing craft were used to provide additional constraints [14].

3.4 (c) Dynamic Stability Tool

The objective of the Dynamic Stability agent is to minimize trim to reduce porpoising effects. Porpoising has been shown to depend strongly on trim angle [15]. A critical trim value can be calculated that estimates when porpoising will occur [16]. In order to stay away from this region, calculated trim should remain below this value. Trim calculations were made using methods provided in Faltinsen's "Hydrodynamics of High-Speed Marine Vehicles" [17]. The critical trim value was used as a constraint for the Dynamic Stability agent.

3.4 (d) Weight Tool

The objective of the Weight agent is to minimize a weight criteria value that ensures displacement is greater than the weight estimate. The lightship weight estimation uses a modified Karyayanis method [18,19]. Fuel weight is calculated using the provided speed and range. The payload weight is provided as an input. The total estimated weight is compared to the full load displacement. The first constraint requires that there is positive buoyancy as well as restricting the total buoyancy to certain value. The second constraint restricts the draught to be within a small percentage of the chine height. The draught is calculated using the geometric properties of the planing craft and the full load displacement associated with those dimensions.

4. SCREENING EXPERIMENT

When there are many different potential factors involved in an experiment, screening can be used to reduce the number of design parameters. This is done by identifying important design parameters that affect the overall goal of the experiment [20]. For this research, there were four main goals in completing a screening experiment. The goals were:

1. Determine reasonable initial ranges and ensure feasible regions exist,
2. Determine how long an experiment takes,
3. Determine how many rounds are typical for this type of experiment, and
4. Determine what type of change should be implemented for the experiment.

Before the screening experiment could begin, a complexity metric had to be defined to describe the various design changes that would be implemented. The first three goals are discussed in Section 4.2 and the final goal is discussed in Section 4.3.

4.1 COMPLEXITY METRIC

Complexity is often described as a function of process, not product [21]. When discussing the complexity of a design change in this paper, it is referring to the change to the design process, not the change in complexity of the planing craft design itself. Identifying how complexity affects a design process is important because it usually leads to "fragile designs that are very sensitive to small perturbations" [22]. A definition of complexity that is suitable for this research is "a measure of the uncertainty in understanding what it is we want to know or in achieving a functional requirement" [23].

Although there are different types of complexity, combinatorial complexity is more important for the experiments conducted for this paper. Doerry states, "Combinatorial complexity results from having many dependencies between the design activities" [21]. For the purposes of this paper, a general complexity metric can be identified using basic dependencies between design activities, or agents in our experiments. Braha describes a metric by stating, "An approach to measuring the complexity of design problems themselves has been proposed by Dixon and his colleagues, based upon the coupling between design targets and design variables. The underlying assumption here is that the more coupled the design problem, the more complex it is" [24].

By looking at the coupled nature of the planing craft design problem, a complexity metric can be used to identify different levels of design changes. If a change only impacts one agent, that is not as complex as a change that impacts every agent. If two changes affect an equal number of agents, the higher complexity change is the one that constrains the design more and makes it more sensitive to failure. An example of a more complex change is varying the magnitude of the design change. This was tested and concluded valid during the screening experiment.

4.2 INITIAL DESIGN SPACE EXPLORATION

The initial design space exploration was mainly used to ensure that there were feasible regions of the design space. For logistical purposes, the experiment length and the number of rounds needed for convergence were also identified. A round is defined as a completed negotiation on every design variable. Once all agents provide preferences for each variable, a Chief Engineer determines an updated set range, which initiates another round of negotiations. Additional information on the process itself will be discussed later in Section 6. After completing the screening experiment, it was determined that feasible regions do exist within the design space, each experiment takes about one hour, and five rounds is a typical number required for convergence.

4.3 DESIGN CHANGE SELECTION

There were two general types of changes that were tested in the screening experiment. The first type of change was increasing the magnitude of a design requirement. The design requirements that could be used were speed, range, payload, or significant wave height. The second type of change was restricting a region of the variable space. For example, a requirement for the planing craft to be transported in a C5-Galaxy cargo plane would restrict the beam. Another change could institute a weight limitation for craning. One of each type of change was tested in the screening experiment: speed and a beam restriction. In order to test our hypothesis that the SBD method is robust enough to handle late-stage design changes, the selection of a design change was based on the total impact on all the agents. An increase in speed was selected as the final design change for the experiments based on the total impact on agents and how preferences shifted after a speed change was implemented.

5. DESIGN OF EXPERIMENTS

The hypothesis developed to guide the design of experiments was that the SBD process is robust enough to handle late-stage design changes of varying complexity. Because 'late-stage' can be an ambiguous term, it was important to define this clearly for the experiments. Round 4 was selected for implementing the design change so the impact of the change could be seen in Round 5, typically the final round.

By specifying the implementation round, the only remaining design parameter is the complexity of the change, which was defined earlier as an increase in magnitude of the speed requirement. Three levels of process variables were defined. These levels included no change, a moderate change, and a major change. For the experiments, the speed was set initially to 45 knots. The second level was set to 47 knots followed by a third level set to 50 knots. Results of these design changes are discussed in later sections.

Due to a simplified design of experiments, replications of the experiments could be completed. Replication means repetitions of an entire experiment or a portion of it, under more than one condition" [20]. For the results presented in this paper, there were three experiments required to test all three levels during Round 4. Three replications of these experiments were completed, which means a total of nine experiments were used.

The response characteristic for the experiments is robustness, which is defined as the observed/measured number of times the current set-ranges cannot handle a design change, also defined as a failure opportunity. It is possible that the process can continue after a failure opportunity occurs by reopening set-ranges to regain feasibility.

6. HAFL DESIGN TOOL

To facilitate the use of the SBD method for ship design, a hybrid agent fuzzy logic (HAFL) design tool was originally developed by Dr. David Singer [25]. Since the initial development of the design tool it has been further studied and utilized for additional ship design experiments including a modified version for the Navy's Ship to Shore Connector design [1] and preliminary containership designs [26].

The HAFL design tool breaks the SBD process into a hierarchical structure, with a Chief Engineer agent at the top of the structure and functional design agents beneath. The Chief Engineer agent has the responsibility of controlling the cycle time for the SBD process by sending requests for the negotiation of ship design variables to the design agents and then later narrowing the set-ranges of design variables based on results from the HAFL design tool.

For the SBD process the ship design is broken down into independent functional design groups and the groups are represented as design agents in the HAFL design tool. For the preliminary planing craft SBD experiments, the functional design agents were Resistance, Seakeeping, Stability, and Weight. The design agents each had an independent design goal as described in Section 3.4.

The HAFL design tool provides the means of facilitating the set-based communications necessary for a SBD process. Human design agents input preferences for design variables that are described via a set of design values ranging from $[x_{min}, x_{max}]$ utilizing any of three linguistic terms Preferred (*P*), Marginal (*M*), and/or Unpreferred (*U*). The interactions between the human design agents and the HAFL design tool software is accomplished through a Java® based graphical user interface.

Design data, including the linguistic preference information, is inherently uncertain. Wallsten and Budescu state that, "Except in very special cases, all representations are vague to some degree in the minds of the originators and in the minds of the receivers" [27], which can be interpreted to mean that all information is uncertain to some degree. Mendel also states that, "words mean different things to different people, and are therefore uncertain" [28]. Since design information is intrinsically uncertain, it is not appropriate to represent the information in a crisp and concise fashion. Therefore, to capture the uncertainty inherent in design data and set-based communications, the HAFL design tool utilizes Type-1 fuzzy logic (T1-FL). Fuzzy logic was chosen for use in the HAFL design tool as it has the ability to handle uncertainty of the negotiated design variables and linguistic terms [29]. By representing design uncertainty, T1-FL utilizes additional design information to enhance set-based communications during the design process.

In the HAFL design tool, the linguistic preference information of the independent functional design agents was represented using T1-FL membership functions (MFs). A T1-FL MF is any mathematical function. The most common MF curve shapes include triangles, trapezoids, Gaussion, Bell, and Sigmoidal functions. It is typical that when applying FL systems to engineering applications the membership values between adjacent fuzzy MFs strive to maintain a logical summation of membership values to one [29]. Trapezoidal and triangular MFs simplify the maintenance of this desired property and were therefore utilized in the HAFL design tool. In addition, from a cognitive standpoint, as a human design agent it is quite simple to visualize the shape and definition of triangles and trapezoids.

When creating the preference MFs, the design agents specify the location of four defining curve points, *x-ll*, *x-lu*, *x-ru*, and *x-rl*; left-lower, left-upper, right-upper, and right-lower, within the set-range provided by the Chief Engineer agent. The *x*-axis represents design values for the negotiated design variable, $[x_{min}, x_{max}]$. The *y*-axis represents the level of membership in a linguistic preference set, with a value between [0,1]; also referred to as the preference level. Figure 2 shows an example of how the Resistance design agent might describe their preference for the negotiation of the beam design variable, based on their goal of minimizing resistance. Notice how the agent prefers the narrower beam values to minimize resistance and has used the MFs to describe the uncertainty between the transitions from one fuzzy preference MF to the following MF. The individual MFs maintain the summation of membership levels to a value of 1.0 throughout the entire set-range.

Fuzzy logic utilizes set-theory which allows a design value to possess membership in multiple data sets simultaneously. For this research, this implies that a design value can belong to more than one preference set simultaneously, but with varying degrees of membership in each set. For example, at a value of $x \approx 19.5$ m in Figure 2, the Resistance design agent has indicated a preference level of $\mu_P(x) \approx 0.5$ Preferred, and $\mu_M(x) \approx 0.5$ Marginal. This represents the design agent's uncertainty as to whether or not the design value of $x \approx 19.5$ m is *P* or *M*. If crisp-theory was being used the design agent would have been forced to choose only a single preference for the value resulting in either of $\mu_P(x) \approx 1.0$ and $\mu_M(x) \approx 0.0$ or, $\mu_P(x) \approx 0.0$ and $\mu_M(x) \approx 1.0$, meaning the design value would belong completely in one set and out of the other [30].

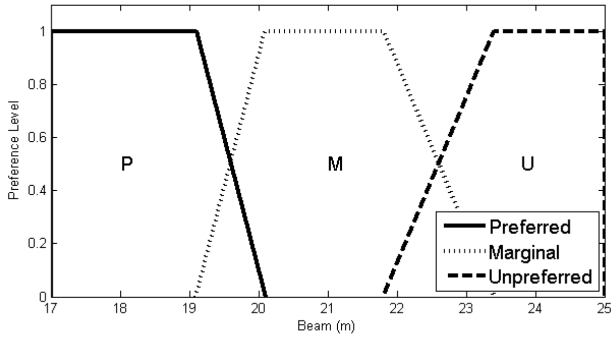

Figure 2: Example of Resistance Agent's Linguistic Preference MFs for Beam Negotiation

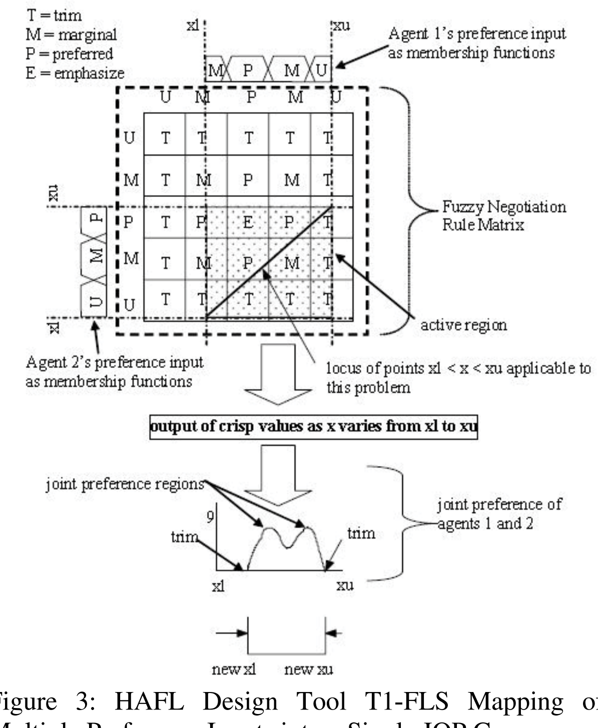

Figure 3: HAFL Design Tool T1-FLS Mapping of Multiple Preference Inputs into a Single JOP Curve

A Type-1 fuzzy logic system (T1-FLS) is capable of mapping an input value of *x* into an output value of *y*. In the HAFL design tool the T1-FLS converts the linguistic preference inputs, coming from multiple design agents whom have independent and often conflicting design goals, into a single joint output preference (JOP) curve.

The JOP curve represents the combination of all design agents' preference information into a single curve. The Chief Engineer agent then utilizes the JOP curve to determine how to appropriately reduce the set-ranges of the negotiated design variables. Figure 3 shows an abbreviated example of the HAFL design tool process.

The HAFL design process displayed in Figure 3 shows two design agents with conflicting linguistic preference information as input into T1-FLS. The input information describes the agents' preference for the negotiation variable set-range values of $[x_{min}, x_{max}]$. The FLS sweeps across the set-range from minimum to maximum activating rules from a fuzzy logic rule bank based on different combinations of the preference inputs. The activated rules are then centroid defuzzified to a crisp preference value. As the process is repeated for every value x_i within the set-range a continuous curve is produced representing the negotiated preference for all design values. This curve is referred to as the JOP curve. The Chief Engineer design agent uses the JOP curve information to determine how to reduce the set-range for a subsequent negotiation round. The reduction process is illustrated in Figure 3 where the set-range is reduced to the "*new xl*" and "*new xu*" defining the lower and upper bounds of the set-range for the next negotiation round.

The purpose of this section was to familiarize the reader with the concepts of the Chief Engineer agent and the independent functional design agents of the HAFL design tool, as well as to outline the methodology of the tool. This section provided a general introduction to some T1-FLS and set-theory terminology. If the reader wishes to learn more about T1-FL and fuzzy logic set-theory references [30] – [33] are suggested.

7. EXPERIMENT RESULTS

The SBD experiments were conducted over the course of three days with the help of eight volunteers. Volunteers were rotated to multiple agent positions depending on availability to change the conditions of each experiment replication. The Chief Engineer role for each experiment was completed by the authors as a detailed understanding of the SBD process was needed for this role. After completing the experiments, confirmation of convergence, agreement between replications, and how the SBD process handled design requirement changes in Round 4 were analyzed.

7.1 CONFIRMATION OF CONVERGENCE

Before looking at how the implemented design changes affected the SBD process, it is important to identify the baseline experimental results without a design change. Three tests were conducted without implementation of a design change. Figure 4 shows a general convergence for the variable beam with no design changes implemented. The three axes show the beam values, the JOP level, and the round number. Starting from the back of the figure in Round 1 and moving forward to Round 5, the narrowing of the set-ranges can be seen. Also, as certain values of the variables became infeasible and the Chief Engineer reduced the sets, the preference levels changed based on updated evaluations by the agents involved; this too can be seen in Figure 4. Even though there seems to be a preference for higher beam values in Round 2, the preference changes in the next round. The change in preference is caused by the combination of how the other design variable set-ranges changed and the updated overlapping feasible region that exists between agents.

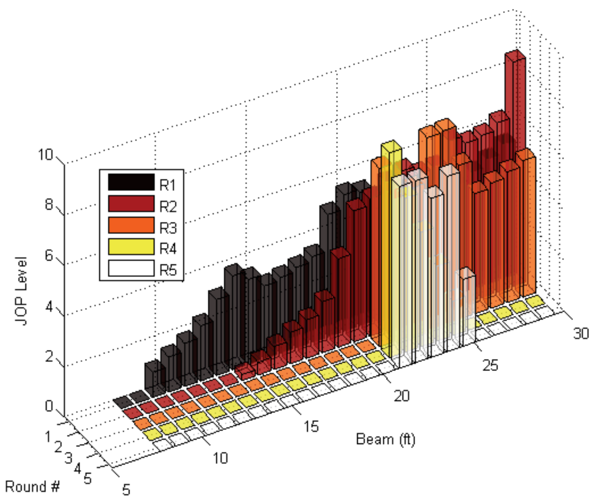

Figure 4: Beam Convergence with No Design Change

Narrowing of the set-ranges for every design variable occurred in all experiments at the end of each round. The set-reduction was controlled by the Chief Engineer agent. The rate of convergence varied for each variable, which is mainly due to the impact of that variable on the agents' objectives. For instance, the deadrise remained open longer than the other variables. This was because most deadrise values were feasible initially and deadrise did not substantially influence the objectives. As the other variable sets narrowed, fewer deadrise values were feasible, which caused it to narrow to a smaller range of values.

7.2 AGREEMENT BETWEEN REPLICATIONS

Replications, as mentioned earlier, are important to test for experimental error. Although narrowing occurs for all variables in every experiment, the convergence rates and final variable ranges for replications of the same experiment may vary. Variance occurs due to the different conditions for each replication including different volunteers controlling agent roles and the approach taken by the Chief Engineer. The type of error associated with these different conditions is mostly random error that is beyond experimental control. After reviewing the JOP curves, for the experiments used in this paper, some variation of set-ranges and convergence rates could be seen for the different design variables. Even with this variation, there are certain areas of the design space that the variables tend to move towards as the design process progresses.

7.3 HANDLING DESIGN CHANGES

The main objective of this paper was to evaluate how the SBD process handles late-stage design changes. The two magnitudes of speed changes affected the process in different ways. Also, the design changes impacted the preferences of agents for certain variables more than others. This section first looks at how agent preferences are modified when a design change is implemented. Then JOP curves for all rounds in the experiments are used to show how the SBD process can handle certain magnitudes of changes. Finally, how the SBD process handles failure opportunities caused by design changes is analyzed.

7.3 (a) Agent Preference Modification

The membership functions (MFs) generated by each agent are combined through FL processes to make JOP curves used by the Chief Engineer who then reduces set-ranges. After using their assigned tool to evaluate the design space within the set-ranges, the agent generates MFs to define preferences for regions of the set-range. Figure 5 shows MFs generated by the Resistance agent for the length variable throughout several negotiation rounds, including the implementation of a major change in required design speed during Round 4. Starting from the top, Figure 5 shows the Resistance agent's preference MFs from Round 3 through Round 5 length negotiation. Solid lines represent the boundaries of preferred regions; dotted lines represent marginal regions; and dashed lines represent unpreferred regions. The labels P, M, and U also correspond to the regions described above.

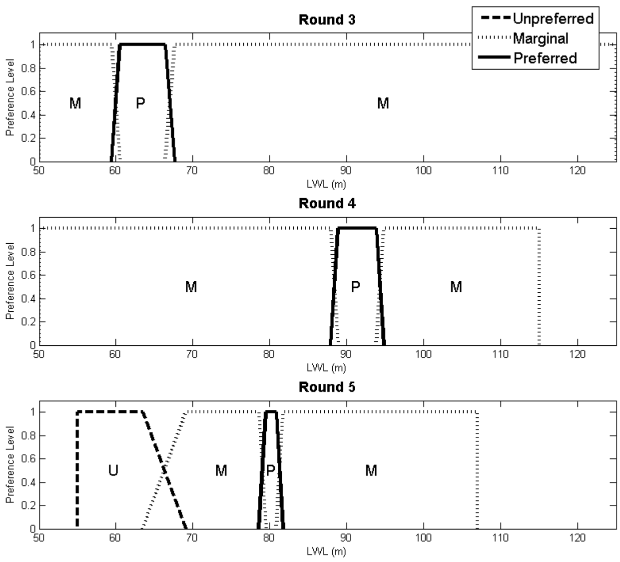

Figure 5: Resistance Membership Function for Length

It can be seen in Figure 5 that in Round 3 there is a strong preference towards values roughly between 60 and 70 feet. After the major design change was implemented in Round 4, the preference region shifted to between 90 and 95 feet. After further negotiation in Round 5, an unpreferred region develops and the preferred region moves slightly towards a value of 80 feet. The scales for length on each round plotted in Figure 5 are the same. This shift in preference can also be seen in the JOP curves in Figure 6. The Resistance agent had the most influence in the shift seen in Figure 6. This makes sense from a ship design perspective because as the speed requirement increases, resistance can be further reduced by increasing the length.

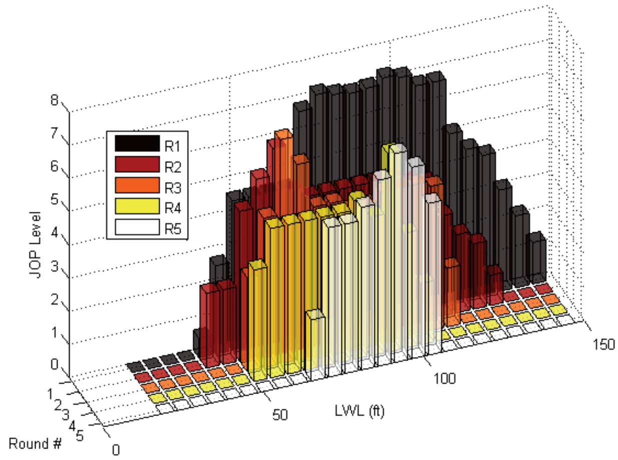

Figure 6: Length JOP Plot with Major Change

7.3 (b) Effects of Varying Magnitudes

Out of all the experiments used for this paper, only one caused a failure opportunity. All other experiments showed that the current set-ranges could handle varying magnitudes of design changes. As mentioned in the previous section, agent preferences are modified depending on the change implemented; either a reduction in set-ranges or a change in design constraints. The agent preferences are then combined via FL to generate a JOP curve similar to the one in Figure 4. The JOP curves can, in addition to showing convergence, show how the preferences have been modified since the implementation of the design change and what direction set preferences are moving towards in the design space.

For the moderate change from 45 to 47 knots, all experiments showed that the SBD process could handle the design change. Figure 7 shows how preferences are modified after a moderate change is implemented. The LCG set-ranges narrow in Figure 7 through the elimination of the infeasible higher values. As the rounds progress, a bi-model preference became more distinct. After the speed was changed from 45 to 47 knots in Round 4, the bi-modal preference shifted to lower values. In the final negotiation round, the higher values were further reduced and the lower preferred mode dominated.
The major design changes constrained the solution space more than the moderate changes discussed above. For

the major change, the speed was increased from 45 to 50 knots. Figure 6 shows the length preferences with a major change to 50 knots occurring in Round 4. It can be seen from the Round 4 preferences that the increase in speed made the most preferred region from Round 3 shift to larger values. Round 5 preferences confirm that the preferred region continues to be in the new direction determined after the change. Figure 6 along with the other major change experiments show that as speed increases, higher lengths are preferred. This trend makes sense from a ship design perspective as well. High level trends such as how speed changes affect variable values can be very helpful for decision-makers in the Chief Engineer role.

The shift of preference displayed in Figure 7 shows that by keeping the ranges of the design variables open longer, the SBD process can handle these modified preferences caused by design changes. Knowing how a change affects the direction of the design can help make proper and informed decisions about future plans. For example, by looking at Figure 7 and seeing the shift in preference, it might be beneficial to reopen the set at the lower end to explore more of the design space in the preferred region. From Figure 6, it can be seen that the design change reduced the set at the lower end, which could be used to reopen the upper set-range to further explore the design space in that preferred region.

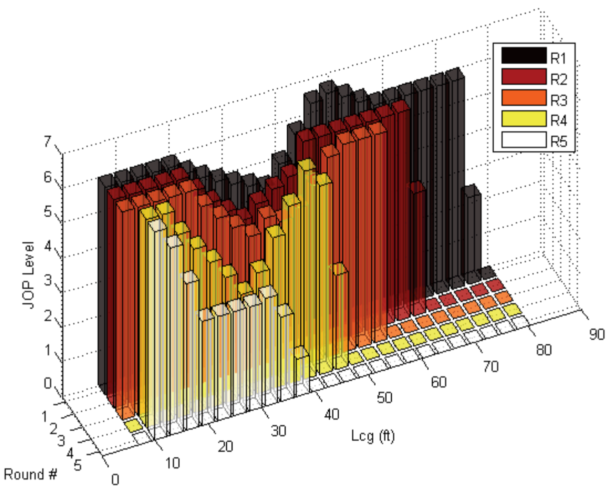

Figure 7: LCG JOP Plot with Moderate Change

7.3 (c) Handling Failure Opportunities

At some point a design change will be too large for the current set-ranges to handle. This occurred in one experiment with a major speed change implemented in Round 4. Figure 8 shows the beam preference with a failure opportunity occurring in Round 4 after a speed change from 45 to 50 knots. The first three rounds are similar to the preferences in the unchanged case provided in Figure 4. Round 3 preferences are mainly towards values between 20 and 25 feet, which is the same preferred range from the unchanged experiment. After the speed increase is implemented, the Resistance agent unpreferred all values in the set. This meant that the narrowed set was completely infeasible.

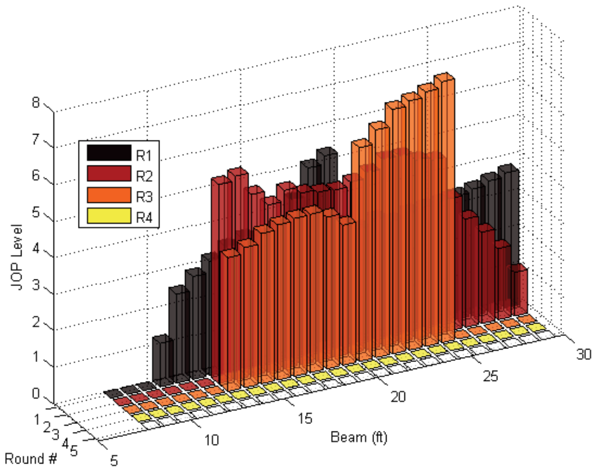

Figure 8: Beam JOP with Failure

Even when a failure opportunity occurs, the SBD process can still be used to quickly and easily redirect the design to the feasible space. This is done by reopening the sets to previous values that were feasible. During the experiment where the failure opportunity occurred, the Chief Engineer reopened the set-range to the previous Round 3 values and asked agents to re-negotiate the variables. Figure 9 shows the beam preference with failure and then the reopening of the set in Round 5. The Round 5 data shows that by reopening the sets, a feasible region can be found. Along with being in a feasible region again, the preferences show a large shift; much lower beam values are now preferred. From a ship design perspective, speed increases would correspond to preferring lower beam values.

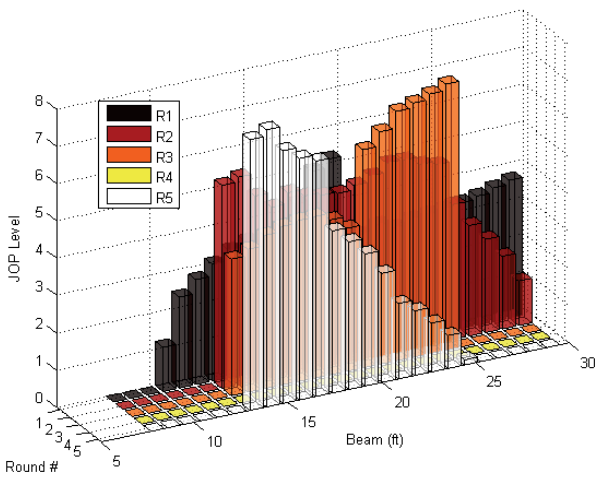

Figure 9: Beam JOP with Failure and Re-Negotiation

Identifying failure opportunities and how the SBD process handles these situations are important components of a set-convergence strategy. While expanding sets during the SBD process is not recommended, special exceptions such as a good improvement idea, an error, or requirement change might dictate its use.

8. CONCLUSIONS

The results of the experiments presented in this paper show how the robustness of the SBD process can handle late-stage design changes. The robustness of the process comes from the ability to delay decisions and keep sets open longer. Also, by being able to reopen sets after a failure opportunity occurs, feasible regions can be located and the new design direction can be found. The experiments show that more complex design changes can further constrain the design process. One of the most important conclusions made from the experimental results is that regardless of the complexity of a design change, the SBD process can show how a change affects the design and where the new design direction should be. This paper identifies a special occurrence during the SBD process defined as a failure opportunity, which requires additional research to understand. Determining if such occurrences can be predicted and what triggers them are topics that need to be explored further. Also, additional intended research includes evaluating the impact of implementing a design change at various times during the design process as well as additional statistical analysis to determine experimental error quantitatively.

9. ACKNOWLEDGEMENTS

We would like to thank Kelly Cooper from the Office of Naval Research for providing support for this project. We would also like to thank contributors and the volunteers that participated in our experiments: Valerie Barthelemy, Brian Cuneo, Fang Dang, Charles Dorger, Greg Filip, Justin Gillespie, Dr. Kevin Maki, Nathan Niese, Al Ogdon, and Bill Rosemurgy.

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