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A HYBRID AGENT APPROACH FOR SET-BASED CONCEPTUAL SHIP DESIGN

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Abstract

Advanced marine design, particularly in the United States, advocates the use of cross-functional design teams, or Integrated Product Teams (IPT's), who will undertake a concurrent engineering approach to all phases of ship design. Further, the study of the world-class Toyota automotive design process has highlighted the potential of a set-based design approach in concurrent engineering to provide a greater probability of achieving a global optimum for the overall design. A hybrid human-computer agent approach is introduced to facilitate set-based conceptual ship design by a cross-functional team of naval architects and marine engineers. The disciplinary/technical specialists are organized and tasked as agents within a design network that can be either be co-located or interconnected across the web. Computer agents are introduced between each pair of human design agents to facilitate their communication and negotiation. A systematic market approach, developed in the Defense Advance Research Projects Agency (DARPA) sponsored Responsible Agents for Product-Process Integrated Design (RAPPID) project, was utilized as an initial approach to facilitate this team, set-based design. The conceptual design of a hatch-covered, cellular, feeder container ship was undertaken by a team of student design agents to assess the effectiveness of this design approach. The design process converged within one six-hour design session indicating the promise of a hybrid agent approach in future marine conceptual design efforts.

Introduction

The conceptual design of ships is an exemplar of complex early stage design in which a wide range of technical, physical, and economic issues must be considered and balanced to achieve an optimum design. This design problem is constrained by multiple, interacting physical and technical constraints. Efforts to use formal optimization in this context whether classical nonlinear programming, multidisciplinary nonlinear programming (MDO), goal programming, or genetic algorithms have generally not proven to be of significant practical value. This occurs because the mathematical models compatible with these numerical methods must necessarily simplify and constrain the problem to such a degree that important real considerations and issues are lost.

Advanced design in the United States has begun to emphasize the use of a multidisciplinary team-based concurrent engineering approach. Notable initial successes have been in the automotive (Chrysler Viper, Ford Mustang) and aircraft industries (Boeing 777). Integrated Product Teams (IPT's) are advocated for future naval ship design (1). Core cross-functional design teams are co-located or linked in a virtual environment to perform the overall design task. The human designers as a cross-functional team are able to comprehend, process, and negotiate the complex range of issues and constraints relevant to a particular design. Advanced simulation-based design (SBD) techniques are also being developed to provide the designers with faster and more reliable results about the physical performance and manufacture of the design. In these advanced design environments, the ability of the designers to communicate and negotiate about the design decisions needed to reach a globally optimum design will likely become the limiting factor.

Team-Based Concurrent Engineering Design

There is a move toward the use of team-based concurrent engineering within ship design in the United States. Notable initial studies have been undertaken by Bennett and Lamb as part of the National Shipbuilding Research Program (2) and by Keane and Tibbitts within the U. S. Navy ship design community (1). Whether labeled Integrated Product Process Design (IPPD) teams or Integrated Product Teams (IPT's), these teams seek to bring together at the earliest stages of design the representatives of engineering, manufacturing, marketing, training, life-cycle support, operations, purchasing, suppliers, etc. to consider concurrently all aspects of the ship's life-cycle so that a global optimum can be approached. The U.S. Navy is currently emphasizing the minimization of total ownership costs. A commercial venture might seek to minimize the Required Freight Rate (RFR). The Shipbuilding Policy/Build Strategy approach to ship design and production advocates that many concurrent engineering considerations be resolved in developing a standard approach to designing a given class of vessels and in rationalizing the production system of the shipyard in advance of developing a specific design (3,4).

These concurrent engineering design teams are usually co-located, but will also be brought together virtually over the internet in the future. The ability of these teams to communicate and negotiate design decisions is a critical factor in the design process.

Traditional Point-Based Ship Design

The traditional approach to communicating the initial ship design process has utilized the "design spiral" since this model was first articulated in the 1959 (5). This model emphasizes that many design issues of resistance, weight, volume, stability, trim, etc interact and these can be considered in sequence, in increasing detail in each pass around the spiral, until a single design which satisfies all constraints and balances all considerations is reached. This approach to design can be classed a point-based design since it is seeking to reach a single point in the design space. The result is a base design that can be developed further or used as the start point for various tradeoff studies. A disadvantage of this approach is that while it produces a feasible design it may not produce a global optimum.

Set-Based Design

The design and production of automobiles by Toyota is generally considered world-class and it is, thus, subjected to considerable study. The study of the Toyota production system led to the evolution of the conceptualization of the Lean Manufacturing (6). The Japanese Technology Management Program sponsored by the Air Force Office of Scientific Research at the University of Michigan has more recently studied the Toyota approach to automobile design (7, 8). The process produces world-class designs in a significantly shorter time than other automobile manufacturers. The main features of this design process include:

- broad sets for design parameters are defined to allow concurrent design to begin,
- these sets are kept open much longer than typical to reveal tradeoff information,
- the sets are gradually narrowed until a more global optimum is revealed and refined.

This approach illustrated in a sketch produced by a Toyota manager in Fig. 1. This design approach has been characterized by Alan Ward as Set-Based Design. It is in contrast to point-based design or the common systems engineering approach where critical interfaces are defined by precise specifications early in the design so that sub-system development can proceed. Often these interfaces must be defined, and thus constrained, long before the needed tradeoff information is available inevitably resulting in a sub-optimal overall design. The simple example is the competition between an audio system and a heating system for volume under the dashboard of a car. Rather than specify in advance the envelope into which each vendor's design must fit, they can each design a range of options within broad sets so that the design team can see the differences in performance and cost that might result in tradeoffs in volume and shape between these two competing items.

The set-based design approach has a parallel in the Method of Controlled Convergence conceptual design approach advocated by Stuart Pugh (9).

A Hybrid Agent Approach to Design

Agents are elements of computer code with elements of perception, intelligence, and adaptability capable of taking independent action. This is in contrast to earlier functions and subroutines that have a programmed function and are called by code to perform that task. This is also in contrast to objects that have data and functionality and can be instantiated within code to carryout these tasks. Networks of simple agents can each perform their specific, assigned tasks and an overall result can emerge from the interactions of the group of agents. Agents can observe system operation and act when necessary.

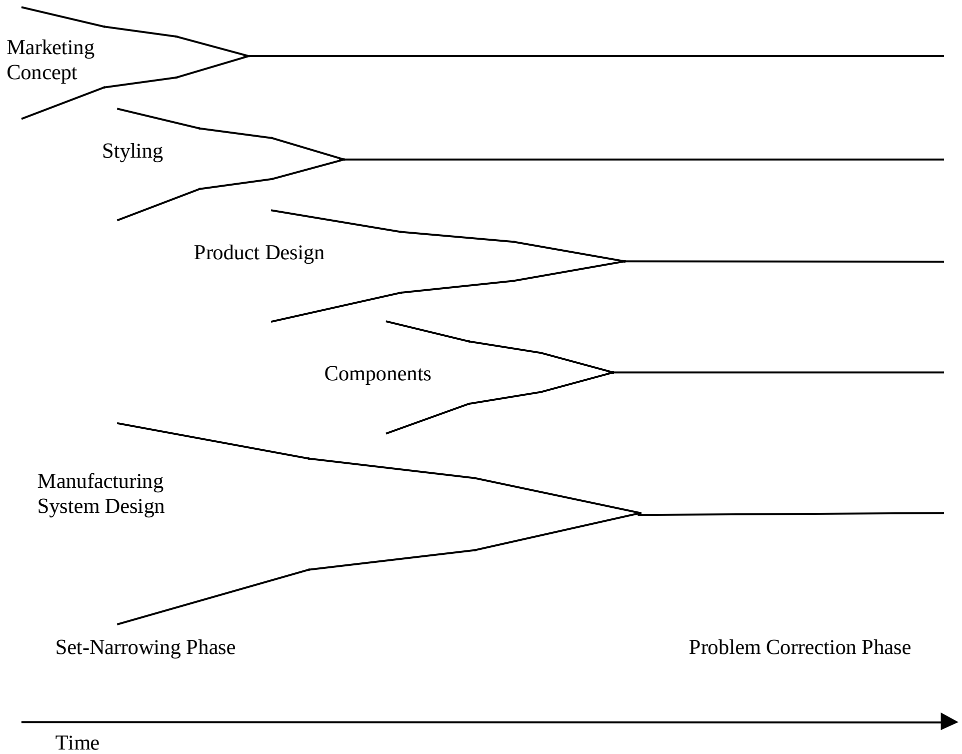

Figure 1. Parallel Set Narrowing Process Sketched by a Toyota Manager (8)

In this work, a hybrid agent approach is utilized. It is felt that problems as complex as ship design will continue to require the expertise, perception, and judgement of the human designers. Using an agent model, however, these designers can be organized and tasked as a network of agents based upon their technical specialty or particular role. Further, computer agents can be introduced between each pair of design agents to facilitate their critical communication and negotiation about the design. This concept results in a hybrid network of human and computer agents.

In the remainder of this paper, the design task of interest is the preliminary, parametric, bid-response design for a feeder container ship. The design team has developed basic design standards and the approach for the design and arrangement of feeder container vessels in the range that their company intends to compete through the development of their Shipbuilding Policy and Build Strategy elements. The shipyard has received a brief performance specification designating the capacity and a speed of vessel indicated by the owner's transportation studies. The goal is to provide a preliminary sizing of a vessel that will provide this function a minimum RFR. In the following, the organization of a design team as a network of agents, a systematic market approach for design negotiation, and the function of the computer agents are described. An initial experiment using this approach is then summarized.

Agent Definition

The naval architects and marine engineers in a preliminary design team can be assigned specific task as agents within a design network. The negotiation mechanism to be used in this example involves a systematic market economy in which design parameters are bought and sold in specific markets. The designers express their desires through their bid or utility functions and trade in dollars that allow all parameters to be valued on a common basis. The task of interest is the parametric stage preliminary design of the vessel for which the shipyard must respond with a bid. The design team is brought together for a day to size the vessel and establish the basis for the bid response. The design agents are each tasked with a portion of the design process and provided with design tools and data to support this work.

The overall network of design agents is shown in Fig. 2. Seven design agents are utilized in this initial investigation. The Chief Engineer, at the upper right, acts as the Voice of the Customer and buys performance parameters from the other agents. In this case, four performance parameters are utilized: the service speed V_k of the vessel on trials at 85% Maximum Continuous Rating of the machinery, the TEU capacity of the vessel, the transverse GM_t as a measure of initial stability, and Clarke's Turning Index P_C as a measure of vessel turnability (10). Other performance characteristics could obviously be included. An implied eighth agent, at the lower left, is the Shipbuilder or the shipyard Production Department which will provide the vessel at a total ship capital cost which is the total of the machinery related cost C_m, the structure related cost C_s, and the outfit related cost C_o. These are implemented through capital cost estimation equations included in the design process. The RFR being optimized by the Chief Engineer also includes operating costs, so there are also an implied markets for the machinery related operating costs Cop_m and the other operating costs Cop_r required by the ship design.

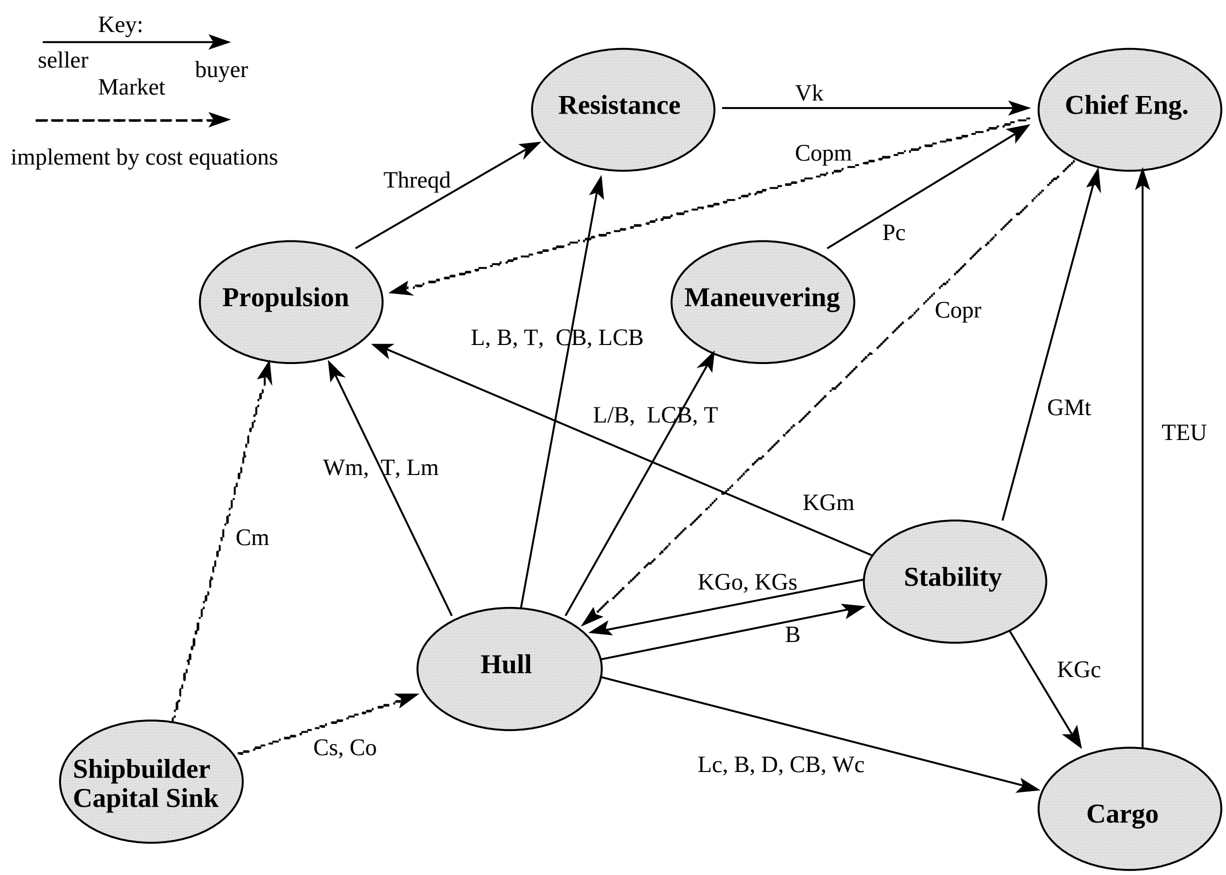

Figure 2. Agent Interaction Diagram

Definition of Conceptual Design Agents

As shown in Fig. 2, the design agents are defined in two hierarchical levels. Four agents are responsible for providing the performance parameters to the Chief Engineer; i.e., Resistance provides speed, Maneuvering provides turnability, Stability provides GM_t, and the Cargo agent provides the TEU capacity. The two agents in the second tier provide the machinery and propulsor needed to provide the total propeller thrust required by the Resistance agent and provide the overall hull needed to meet the needs of the design. The seven design agents are defined in detail in Table 1, which lists the design role or objective and constraint responsibility of each agent. It also lists the parameters that each agent buys or sells. The agent with the greatest at stake with respect to the associated constraints is the seller of the particular parameter. The agents are each tasked to act altruistically so that no profit is made; i.e., sell revenues balance the buy obligations to the other agents. The parametric design tools provided to each agent are also listed.

The Chief Engineer agent is the overall leader of the design team and serves as the Voice of the Customer. He or she seeks a minimum RFR design (as opposed to a minimum cost design that would more typically be the shipyard's objective in developing a bid response). The computational tool available is a RFR calculation based upon the parameters of the design.

The Resistance agent is responsible for satisfying the hydrodynamics physics and sells service speed to the Chief Engineer. To achieve this speed, this agent must buy total propeller thrust from the Propulsion agent, but can also participate in the markets for the hull parameters that will affect the required thrust; i.e., length, beam, draft, block coefficient, and longitudinal center of buoyancy. The computation tool available is the Power Prediction Program (PPP) which implements Holtrop and Mennen's regression-based resistance prediction method for displacement hulls (11, 12, 13).

The Maneuvering agent is responsible to provide turnability to the Chief Engineer and decide whether or not to include a bow thruster in the design. To provide turnability, the agent sizes the rudder based upon a parametric model related to ship draft and participates in the markets which will affect the maneuverability; i.e., length/beam ratio, longitudinal center of buoyancy, and draft. The computational tool available is the Maneuvering Prediction Program (MPP) which implements and extends the work of Clarke et al (10, 11).

The Stability agent is responsible for ensuring that the vessel provides the minimum GM_t required by the Chief Engineer. To provide this stability, the agent must buy beam from the Hull agent using revenues acquired by selling vertical centers of gravity to the Cargo, Propulsion, and Hull agents. The computational tool available incorporates preliminary weights and centers estimation models from Watson and Gilfillan (14) and Kupras (15) into a transverse weight summation spreadsheet.

The Cargo agent is responsible for ensuring that the vessel provides the TEU capacity required by the Chief Engineer. To provide this, the agent must buy cargo box length L_c, beam, depth, block coefficient, and cargo weight from the Hull agent and buy cargo vertical center of gravity from the Stability agent. The design tools available are a matrix or catalog of cargo box dimensions for various choices of container configuration within the hold and on deck above the hatch covers assuming a prismatic hull with two containers missing in each stack at the lower corners. This agent also has a parametric regression model (or alternatively an Artificial Neural Network) for the total TEU capacity that reflects the full tapering effect of the hull on the container block.

The Propulsion agent is responsible to provide the propulsion machinery necessary to produce the total propeller thrust required by the Resistance agent. The agent must buy machinery box length Lm, draft (influencing propeller diameter), machinery related weight and vertical center of gravity. Implied markets include the capital purchase of the machinery and the machinery related operating costs. The design tools available are a catalog of MAN B&W and Wartsilla medium-speed diesels and the Propeller Optimization Program (POP) which uses the Nelder and Mead Simplex Search and External Penalty Function (16) to design the optimum Wageningen B-Screw Series propeller subject to diameter and cavitation constraints (11, 17). With the overall workload assigned to this agent, he/she is supported by a propeller design assistant.

The Hull agent is responsible for the overall integration of the hull dimensions and arrangement and for ensuring that the total weight equals the displacement. This agent is the seller in all of the hull sizing and weights markets. The Hull agent must also buy the vertical center of gravity of structure and outfit it will provide. Implied markets include the capital purchase of the structure and outfit portions of the ship and the non-machinery related operating costs. The provided computational tool incorporates preliminary weights and centers estimation models into a longitudinal weight summation spreadsheet. With the overall workload assigned to this agent, he/she is supported by an arrangements design assistant.

Table 1. Definition of Design Agents

Agent: Chief Engineer; Voice of the Customer	
Objective:	Provide functional requirements to customer at minimum Required Freight Rate
Buys:	V_k, P_c, GM_t, and TEU
Sells:	Cop_m, Cop_r (implemented through equations in RFR calculation)
Constraints:	customer's functional requirements
Tools:	RFR calculation
Agent: Resistance	
Objective:	Provide required ship speed
Buys:	L, L/B, T, C_B, LCB, and Th_{reqd}
Sells:	V_k
Constraints:	hydrodynamics
Tools:	Power Prediction Program (PPP)
Agent: Maneuvering	
Objective:	Provide required turning capability; set rudder/thruster size
Buys:	L/B, LCB, and T
Sells:	Clarke's Turning Index P_c
Constraints:	horizontal plane maneuvering dynamics
Tools:	Maneuvering Prediction Program (MPP)
Agent: Stability	
Objective:	provide required initial transverse stability
Buys:	B
Sells:	GM_t, KG_m, KG_o, KG_s, and KG_c
Constraints:	transverse equilibrium
Tools:	transverse portion of Weights I summary
Agent: Cargo	
Objective:	provide required TEU/FEU capacity
Buys:	L_c, B, D, C_B, W_c, and KG_c
Sells:	TEU
Constraints:	cargo block geometry
Tools:	cargo block catalog; TEU capacity model that includes the effects of longitudinal hull taper
Agent: Propulsion	
Objective:	provide required propeller thrust; choose engine; design propeller
Buys:	L_m, W_m, T, and KG_m plus C_m and Cop_m (implemented through equations in RFR calculation)
Sells:	Th_{reqd}
Constraints:	propeller hydrodynamics, available Wartsilla and MAN B&W medium speed diesels
Tools:	engine catalogs, Propeller Opt. Program (POP); supported by propeller designer
Agent: Hull	
Objective:	Provide required hull volume and required outfit; ensure even keel
Buys:	C_s, C_o, Cop_r (implemented through equations in RFR calculation)
Sells:	L, L/B, B, T, D, C_B, LCB, W_m, and W_c
Constraints:	Archimedes Principle, zero trim
Tools:	longitudinal portion of Weights I summary; supported by ship profile manager
Agent: Shipbuilder/Capital Sink	
Objective:	provide specified vessel to design agents
Buys:	nothing
Sells:	vessel for price that is the sum of C_m, C_s, and C_o
Constraints:	sink
Tools:	building cost estimating equations; implemented directly in RFR calculation

Market and Auxiliary Variables

The work of the agents requires that the market parameters be precisely defined in advance. Each agent also needs to know the value for additional auxiliary variables in order to carryout needed computations and analyses. The choice of these auxiliary variables is the responsibility of specific agents based upon their design decisions or the results of design computations that they perform. The auxiliary variables are not part of the markets, but must be defined and communicated to other agents as needed. The definition of the market variables and the information flow of the auxiliary variables among agents are summarized in Table 2.

Systematic Markets and RAPPID

A designer seeks to embed a set of *functions* in an object with specified *characteristics* (e.g., weight, materials, power consumption, and size). Conflicts arise when designers disagree on the relation and importance of the characteristics of their own functional pieces and the characteristics of the entire product. There is no disciplined way to tradeoff characteristics such as weight and power consumption against one another. The problem is the classic dilemma of multivariate optimization. Analytical solutions are available only in specialized niches. As a result, the state of current practice is that tradeoffs are resolved in ways that do not optimize for the best overall system and manufacturability

The Responsible Agents for Product/Process Integrated Development (RAPPID) project developed an approach to design that helps human designers manage product characteristics across different functions and stages in the product life cycle (18, 19). These agents participate in a design *marketplace* where the goods being traded represent the design characteristics of each of the product components. By representing the explicit cost and value of these design characteristics in a common currency, the resulting marketplace provides a self-organizing dynamic that may yield more rational designs faster than conventional techniques. These markets allow individual designers to make tradeoffs and narrow sets of design characteristics in a way that leads to better global designs.

RAPPID addresses three core problems in design:

- *Planning*. Design tasks cannot be sequenced in detail. There is generally no way to progress through the design analysis and decision-making in an organized way such that all the information is available when necessary to each designer. Thus, the design spiral.
- *Coupling*. Designers think locally, but they are tightly coupled with other designers. Decisions that one designer makes affect the decisions that other designers have made. This constant need for re-evaluation as a result of changes in the design interfaces can lead to lengthy cycles of iteration and change.
- *Prioritizing*. Designers have no common language for comparing the importance of issues.

In RAPPID, independent agents use set-based reasoning in a design marketplace to address these problems as depicted in Fig. 3. The combination of independent agents (designers) working with set-based reasoning addresses the planning issue. By working with sets or ranges of parameters, designers can work in parallel without waiting for other designers to set the value of some design characteristic they need. Markets provide the means by which many alternatives in a set can be evaluated using a common currency as the comparison. And finally, the RAPPID markets provide information to each designer that allows them to make individual decisions that contribute to globally optimal results much as real markets work to find the best clearing price for a good.

RAPPID Markets

Figure 1 shows an example of agents used in a preliminary ship design and the design characteristics that they trade. One can think of this network as a supply chain. The Propulsion agent sells the required thrust (Th_{reqd}) to the Resistance agent. The Resistance agent buys the amount of thrust it needs from the Propulsion agent as well as aspects of the hull shape which affect resistance from the Hull agent in order to produce the service speed (V_k) the Chief Engineer agent seeks. The

Table 2.
Variable Mapping Among
Design Agents

Agent Tool	Variable	Units	Description	**Chief Engin./** **Customer**	**Resistance** PPP resistance	**Maneuvering** MPP maneuvering	**Stability** Weights I trans. intact stab.	**Cargo** TEU model cargo layout	**Propulsion** POP, catelog prop., engine	**Hull** Weights I longl. sizing, trim
Market Variables	Vk	knots	trials speed at (1-service margin) power	B	S	X			X	X
	Pc		Clarke's turning index	B		S				
	GMt	m	transverse metacentric height	B			S			
	KGm	m	machinery related VCG				S		b	
	KGc	m	cargo VCG				S	B		
	KGo	m	outfit VCG				S			B
	KGs	m	structure VCG				S			B
	TEU		20' container count	B				S		
	Threqd	kN	total required propeller thrust		B				S	
	L	m	LWL, waterline length	X	B	X	X			S
	L/B		length/beam ratio		B	B				S
	T	m	mean designed draft		B	B	X		B	S
	CB		block coefficient	X	B	X	X	B		S
	B	m	beam	X	X		B	B	X	S
	Wm	tonnes	propulsion machinery, fuel, lube oil weight				X		B	S
	Lm	m	length of engine room						B	S
	Lc	m	length of cargo box					B		S
	D	m	depth	X	X			B	X	S
	Wc	tonnes	cargo weight				X	B		S
Auxiliary Variables	w		mean longitudinal wake fraction		O				X	
	t		thrust deduction		O				X	
	etar		relative rotative efficiency		O				X	
	Ar	m^2	rudder plan area		X	O				
	BThr	kN	bow thruster thrust	X	X	O				
	Ncrew		complement	X			O			X
	Ndays		endurance days for stores and water				O			X
	KB	m	vertical center of buoyancy				O			X
	design KG	m	ship vertical center of gravity including margins				O			X
	hdb	m	double bottom height					O	X	
	sfc	t/kWhr	propulsion specific fuel consumption	X					O	
	sloc	t/kWhr	propulsion specific lube oil consumption	X					O	
	no. props.		number of propellers		X	X			O	X
	Dp	m	propeller diameter						O	
	Pb	kW	main engine Maximum Continuous Rating	X					O	
	Cx		maximum section coefficient		X					O
	Cwp		waterplane coefficient		X		X			O
	LCB (=LCG)	%L,+fwd	longitudinal center of buoyancy		X	X				O
	Wo	tonnes	oufit weight				X			O
	Ws	tonnes	structure weight				X			O
	LBP	m	length between perpendiculars	X						O
	DWT	tonnes	total deadweight	X						O
Implied Market Variables	Cm	M$	machinery related capital cost	X					O	
	Cop,m	M$/yr	machinery related operating costs	X					O	
(implemented by cost eqns. in RFR calculation in the initial experiment)	Co	M$	outfit related capital cost	X						O
	Cs	M$	structures related capital cost	X						O
	Cop,r	M$/yr	remainder of operating costs	X						O

Key:
X = input
B = buyer
S = seller
O = output

arrows in the diagram indicate the direction of the sale and the label identifies the market good or design characteristic.

In RAPPID buyers express their preference for an item they are purchasing using a qualitative cost curve. The curve expresses the range of prices the buyer is willing to pay for a set of assignments to a design characteristic. The curve also expresses in general how this preference varies over the range of the design characteristic. The ^ shaped curve in Fig. 4 is an example of a buyer's buy curve. In this example, the buyer is indicating that they would be willing to pay between $100K and

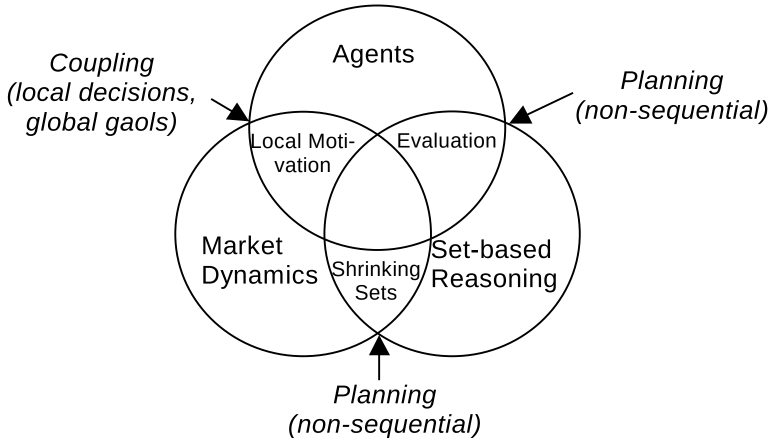

Figure 3. Interaction of Three Concepts in RAPPID

$500K for thrust in the range of 600 to 1600 kN. In general, thrust is more valuable towards the middle of that range than at the ends. Similarly, the supplier can issue a sell bid (superimposed on the buy bid in Fig. 4). The supplier indicates thrust in the range of 600 to 1600 kN ranges in price from $100K to $450K and, in general, its price increases as thrust increases.

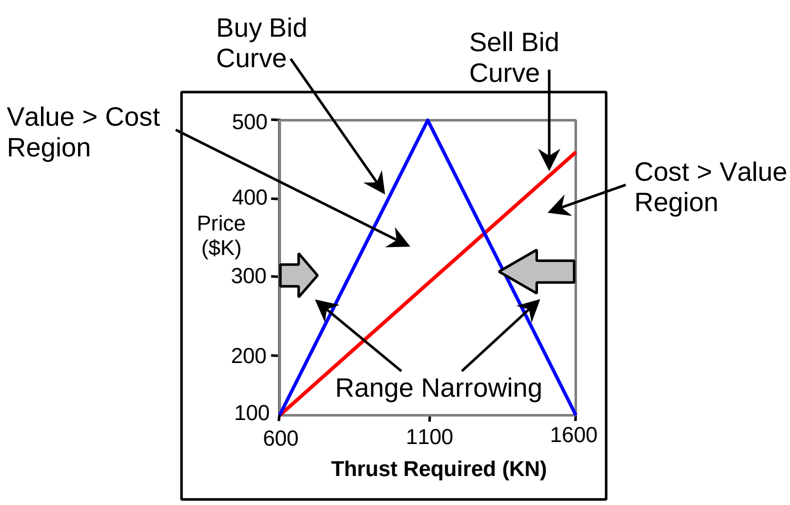

Figure 4. Buy and Sell Bid Curves

Based on this qualitative information, the buyer can begin to make some choices. The ideal thrust would be the point where the difference between the buy and the sell price curves is maximized. This is the thrust that would provide the most value to the buyer for the least price. Since these curves are only qualitative, we cannot identify that thrust value directly from these bids. However one can say that at the high end of the thrust range, the price is most likely much higher than the customer is willing to pay (Cost > Value). It is unlikely that there is a suitable thrust at that end of the range, so the customer can narrow the range down from the high end. One could also remove a small amount from the low end of the range knowing that the maximum difference between buy and sell curves is unlikely to be found at the low end. Once the range is narrowed, the customer and buyer can spend more time analyzing a much narrower range of options. This will result in new bids and possibly new curve shapes. As certain ranges get narrowed down, other ranges will also narrow as a result. Many design characteristics are coupled together so that a compression of one range will cause other ranges to narrow throughout the network. Eventually these ranges will narrow to a single point. At that point the design is complete. In RAPPID no money actually changes hands. The buy and sell curves are used as approximations of cost and preference surfaces to guide the designers in searching for an optimal location in the design space. The use of these qualitative market dynamics in RAPPID is based on research in market-based distributed constraint optimization (20).

RAPPID Market Server

To assist designers in making buy and sell bids and analyzing the market data for places to narrow ranges a RAPPID Market Server as shown schematically in Fig. 5 was created. The market server was designed to work in a wide variety of design environments. It is intended as a tool to assist a distributed team of designers in analyzing their design space, make appropriate trade-offs, and manage the convergence of the design around the final solution. The design histories that it maintains provide a detailed transaction log that can be used to reconstruct the rationale used to make various trade-offs.

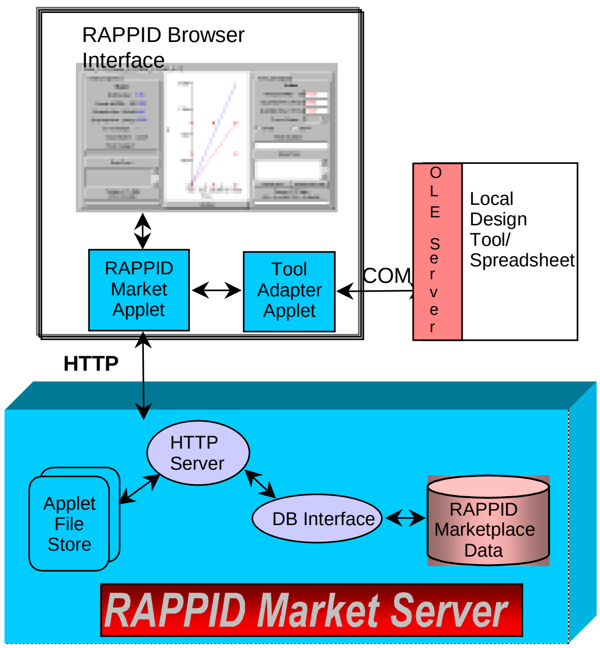

Figure 5. RAPPID Design Market Server

The market server consists of a database server that is accessed through a web interface. The database defines all the markets and the agents and keeps records of all the market transactions. The main web page market summary view (not shown) displays all the current markets and the last buy and sell bids. This provides the designers with a quick view of the state of all the markets. One can quickly identify from this view markets which show the greatest potential for narrowing or which might be the most profitable upon to work.

Detailed information on any individual market is available through a Java applet an example of which is shown Fig. 6. The applet shows the last buy bid for the market in a form on the left. The form on the right details the last sell bid. A simple graph of the two bids is displayed in the middle. The graph provides a visual clue to the designers of how to narrow the ranges to reach the point of greatest value for least cost. If the agent is registered as a bidder in the market, then one of the forms will have editable fields where new bid information can be submitted. The bid includes a small Notes field where the designer can send explanatory information regarding the bid or reference supporting documents.

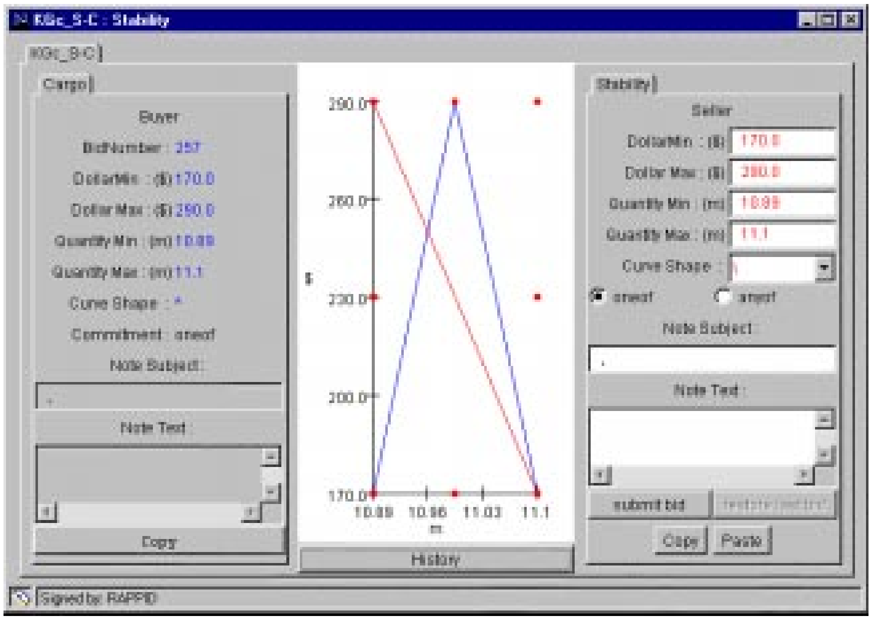

Figure 6. Java Applet for Market Bids

Since designers use many different tools to analyze their design, the RAPPID Market Server is designed to interface through a wide range of standard methods, from the simple clipboard, to more powerful DCOM and CORBA interfaces. This relieves the designer of the burden of manually transferring data between the market server and their design tools.

Hybrid Agent Ship Design Experiment

The Hybrid Agent Ship Design Experiment was conducted in two phases: an initial exploratory experiment and then the more formal Hybrid Agent Experiment.

Initial Exploratory Experiment

The initial exploratory phase was completed in April 1998. This involved the initial evaluation of the Agent concept as a possible approach to preliminary ship design without the use of systematic markets to aid design negotiation. The initial experiment was performed by seven University of Michigan undergraduate naval architecture students using the Undergraduate Marine Design Laboratory of the Department of Naval Architecture and Marine Engineering. The assigned task was, given a set of owner's requirements, to produce a conceptual design of a feeder container ship with the lowest RFR within four hours using a prototype web-based agent communication environment.

The Phase 1 experiment provided a template for the development of the Phase 2 experiment. From the results of the initial experiment, the original agents, their tasks, and their design tools where redefined. The RAPPID systematic market approach was added to experiment with the hybrid agent approach to aid design negotiation. It became clear that each agent's role needed to be well defined using market and auxiliary variables unique with respect to the specific role of the each agent. This can be seen in the variable length. The total ship length is an important variable to many agents. It was found that the agents could be more effective, however, if they were concerned only with that portion of the total length that they could clearly define. Thus, the ship length was broken down into Length of Engine Room, Length of Cargo Box, and total LWL for use by different agents.

Another important conclusion from the Phase 1 experiment was that the workload and level of design analysis sophistication assigned to each agent needed to be balanced across the agents. The original experiment had agents with widely varying workloads and levels of design/analysis complexity. This caused delays in the process since some agents had large amounts of data to analyze while other agents had very little work to do. The act of overwhelming an agent caused that agent to breakdown, thus, hindering the whole process.

Hybrid Agent Design Experiment

In January of 1999, the Phase 2 experiments began. The Center for Electronic Commerce of the Environmental Research of Michigan (ERIM) joined the experiment to adapt its RAPPID systematic markets software to this design problem. The Phase 2 experiments consisted of an initial RAPPID and design software training day, January 16, 1999, and a final experiment day, January 30, 1999. The initial training day was used to help familiarize the design team with the agent-based and set-based design concepts and software environment. The time between the training day the experiment day allowed the individual designers to become more familiar with their particular agent role as well as the RAPPID software. The students in the second experiment were all graduate students with one exception.

The Phase 2 design experiment had essentially the same design goal as the Phase 1 experiment. The primary requirements for the Hybrid Agent experiment where for the students to respond to a request for bid for a conventional hatch-covered, handy-sized feeder cellular container ship for use along the Pacific Northwest feeding to the container terminals in Oakland, CA, and Seattle, WA. The vessel needed to satisfy the following requirements:

- Carriage of 500 TEU (Twenty foot Equivalent Units) with an average weight of 15.0 tonnes with a VCG at 45% of the container height. Uniform loading.
- Alternative FEU (Forty foot Equivalent Units) with an average weight of 20.0 tonnes.
- Endurance of 1600 nm at service speed for fuel, and 20 days for provisions and water
- Maximum length and beam Panamax; maximum draft of 6.0 m.
- Service speed at 85% Maximum Continuous Rating on trials of 16.5 knots.
- Clarke's Turning Index of at least 0.35.
- Minimum GM_T of at least 0.25 m in the uniform load condition.

To establish a starting set for the primary ship dimensions at the beginning of the experiment, regression equations where used to find LBP, B, D, and T as a function of cargo deadweight and ship speed. The mean value produced by the regression equations $\pm 2\sigma$ (regression Standard Errors) which is expected to contain 95.5% of the world fleet was used as the initial set. The initial sets for the primary size variables allowed the agents to begin their particular evaluations. These initial sets can be seen in Table 3.

Table 3. Initial Set Ranges for Primary Size Variables

Variable	Lower Bound	Upper Bound
LBP	100.9 m	149.5 m
LWL	103.9 m	152.9 m
B	16.8 m	24.0 m
D	7.8 m	13.7 m
T	2.6 m	7.4 m

The design experiment was conducted over a period of about seven hours during which the primary variable converged to a final design sizing. This convergence for the LWL sets considered in the negotiation between the Hull agent and the Resistance agent is illustrated in Fig. 7.

Table 4 is the relevant portion of the cargo box geometry spreadsheet used by the Cargo agent. The sheet shows the beam, depth, length of cargo box, container configuration, and total number of containers for a given configuration and length ignoring the effect of the longitudinal taper of the hull. The table has several differently shaded regions that show the convergence of the design during the experiment. The design sets initially included three cargo box lengths, three beams, and three depths. The non-shaded region shows the near final set of cargo configurations.

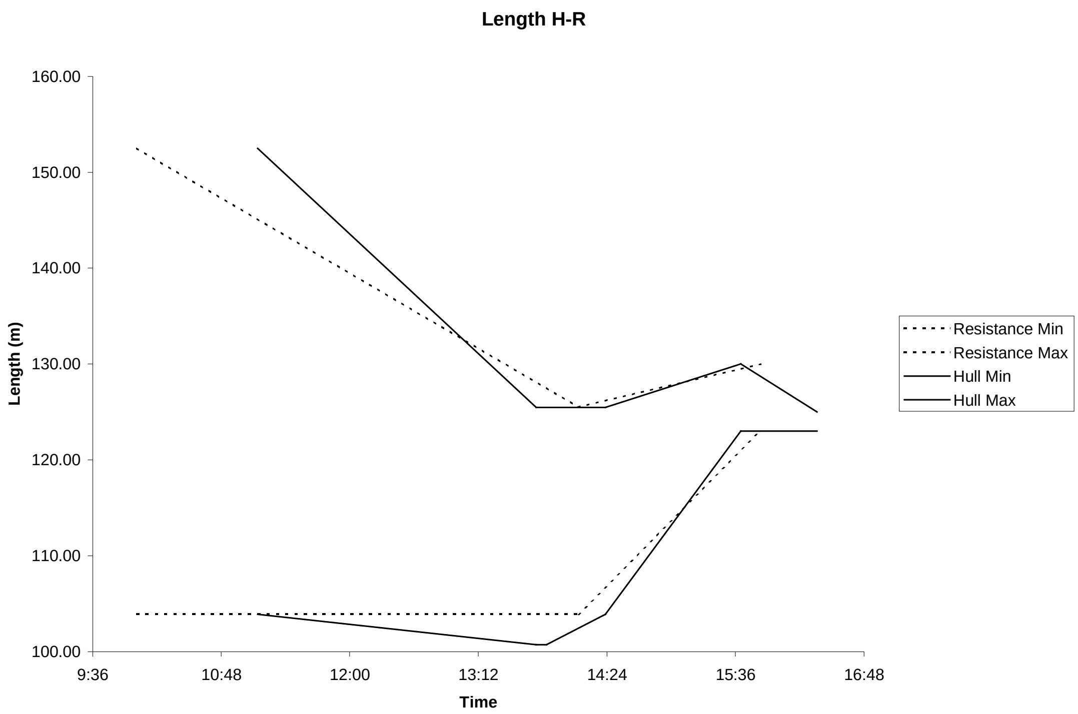

Figure 7. Convergence of Length Market Over Time

The near final set consisted of one beam (22.2 m), two depths (9.96 m and 12.55 m), and two cargo box lengths (69.4 m and 82.92 m). The longer hull was then eliminated since it would provide excessive TEU capacity. Required Freight Rate consideration by the Chief Engineer agent then reduced the set further by eliminating the larger depth so that the design team converged to a beam of 22.2 m, depth of 9.96 m, and a cargo box length of 69.4 m.

Conclusions

A hybrid system of human design agents and intermediate computer agents that can facilitate their communication and design negotiation shows promise as a means of achieving effective conceptual ship design by cross-functional design teams. This fosters a set-based design approach to conceptual ship design. The following specific conclusions are noted:

- The network of agents provides an effective way to organize a cross-functional design team.
- The negotiation across the network provides an effective way to balance the interests of the design team members.
- The negotiation process can improve the reasoning and cross-functional understanding during design tradeoffs.
- A converged marketplace can assess the interaction and design value of different parameters even in the absence of analytical theories.
- The set-based design paradigm replaces design construction with design discovery; it allows design to proceed concurrently and defers detailed specifications until tradeoffs are more fully understood.

Table 4. Relevant Portion of Cargo Box Geometry Spreadsheet

code	NHhold	NVhold	NVdeck	B[m]	D[m]	6 40.96	8 54.48	10 69.40	12 82.92	14 97.84	16 111.36	<=#Columns <=holdlength
6x4+3	6	4	3	19.6	9.96			460	552	644		
6x5+2	6	5	2	19.6	12.55			440	528	616		
6x5+3	6	5	3	19.6	12.55			520	624			
6x6+2	6	6	2	19.6	15.14			500	600			
6x6+3	6	6	3	19.6	15.14			580	696			
7x4+3	7	4	3	22.2	9.96			530	636			
7x5+2	7	5	2	22.2	12.55			510	612			
7x5+3	7	5	3	22.2	12.55		480	600				
7x6+2	7	6	2	22.2	15.14		464	580				
7x6+3	7	6	3	22.2	15.14		536	670				
8x4+3	8	4	3	24.8	9.96		480	600				
8x5+2	8	5	2	24.8	12.55		464	580				
8x5+3	8	5	3	24.8	12.55		544					
8x6+2	8	6	2	24.8	15.14		528					
8x6+3	8	6	3	24.8	15.14	456	608					

Deleted from Beam Reduction
Deleted from Depth Reduction
Deleted from further reduction (Cb concicerations, Chief Engineers requests)

- Set-based design can greatly increase the number of design alternatives considered.
- The process is robust to intermediate design errors. During the experiment the logic used to set block coefficient was incorrect for about half of the design period. When this was discovered and corrected, the sets were still wide enough that the process was able to move forward and reach a converged solution without major rework.
- The recorded market histories permits design logic reconstruction and institutional learning.
- The experiment utilized the qualitative set communication and reduction aspects of RAPPID, but the specific price aspects of the markets did not have an important impact. Part of this was because the design was highly constrained and part was because the process was terminated near the end of the set reduction and did not continue into the refinement phase.

The hybrid agent approach can provide a means to address the potentially limiting design communication and negotiation process in advanced, potentially distributed, cross-functional team design.

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