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Application of Systems Engineering Methodology to the Design of an Agricultural Research Program

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Abstract. In 1991. USDA and EPA agreed to a joint program in Integrated Farm Management Systems (IFMS). In 1992, the Agricultural Research Service of USDA assigned four Systems Engineers to develop concepts for a research program in IFMS. Customer groups representing farmers. researchers, environmentalists, agribusiness, and administrators were interviewed to determine the necessary inputs. outputs, and performance requirements of the system. The inputs were identified as resources and demands for service. The outputs included plans for farm management, research publications, and software. Performance criteria were grouped into three categories; SYSTEM OPERATION. QUALITY of FARM PLANS, and RESEARCH PRODUCTIVITY. Four concepts were developed which met the I/O and performance requirements. The strengths and weaknesses of each concept were identified. The concepts were evaluated under three different hypothetical input scenarios. The CONTRACTS concept had the highest overall performance score across the three scenarios, but the PANELS concept had the highest performance per unit cost value. Sensitivity analyses identified the performance requirements contributing to the QUALITY of FARM PLANS as having the greatest overall impact on the system performance score.

INTRODUCTION

In 1991. Environmental Protection Agency's (EPA) Office of Research and Development and the US. Dept. **of Agriculture's** (USDA) Science and Education office agreed to a joint research and development budget initiative for 1993 in the area of Integrated Farm Management Systems (IFMS). The IFMS initiative was to foster food and fiber production in an enhanced environmental manner through emphasis on application of sustainable agriculture and integrated pest management approaches. A pilot project was to be conducted in the Walnut Creek Watershed near Ames, Iowa: a heavily instrumented. farmer-owned and operated site at which USDA. EPA. U. S. Geological Survey, Iowa State University and other entities were already cooperating on a project to enhance water quality. IFMS was defined as a collection of interacting agricultural management and production techniques applicable to farms and **ranches that incorporates principles and guidelines related to economics, environment, and social acceptance. It includes the concerns of the farmer, krm suppliers, environmentalists, local community, consumers and the public. Protection of profitability for the fanner is to be balanced against maintenance of water quality, concerns for long-term agricultural sustainability, air pollution.** and habitat protection.

In March 1992, a decision was made in USDA's Agricultural Research Service (ARS) to apply the principles of Systems Engineering as described by (Wymore, 1993) to the planning of the IFMS research and development program. During the initial planning phases, 50 separate interviews were conducted with over 150 people representing USDA, EPA, other federal agencies. industry, private enterprise. farmers, economists, sociologists, and environmentalists. The top level **function of the** system, *IFMS. was* **identified** from these interviews as develop alternative, integrated farm management practices that will ensure environmentally safe, economically sound, and socially acceptable agriculture throughout the Walnut Creek Watershed of Central Iowa. Other criteria that were initially defined were the inputs and output of the system, the boundaries of the system. and Performance Requirements upon which the system would be judged. Inputs into the system include demands from the public far a clean environment and productive agriculture (DEMPUBLIC. the Demand of the Public), resources such as time and money (COMMITMENT). individual

		FIGURES OF MEI)		Wgt
1000	SYSTEM OPERATI(		wgt	0.30
	1100	CAPACITY	0.15	
	1200	TIME DELAY	0.15	
	1300	FLEXIBILITY	0.10	
	1400	UNADDRESSED PROBLEMS	0.15	
	1500	AVAILABILITY	0.15	
	1600	RELIABILITY	0.15	
	1700	MAINTAINABILITY	0.15	
2000	PLAN QUALITY		wgt	0.35
	2100	ENVIRONMENTAL	0.40	
	2200	SOCIAL	0.20	
	2300	ECONOMIC	0.40	
3000	RESEARCH PRODUCTIVITY		wgt	0.35
	3100	COOPERATION	0.20	
	3200	RESEARCH ACCOMPLISHMENT	0.80	

Table 1. Performance criteria for the system, *IFMS.*

needs and preferences of farmers to implement new management strategies according to location and site-specific resources (DEMFARM, the Demand of the Farmer), and measurements that will provide information on how well the system ***IFMS*** and the resulting farm designs were operating (FEEDBACK). The system will output alternative farming strategies far the farmer (PLANS) and fulfii the research mission of ARS to conduct original research and transfer technology (COMMUNICATION). The Performance Requirements (Figures of **Merit - FoMs) were used to evaluate the performance of** proposed solutions. **The** Utilization of Resources (costs) were estimated for each concept. A Tradeoff function was **used to determine the** greatest **performance** per unit **cost from among the proposed concepts.**

The system to be designed was perceived to be complex and would be judged by three sets of Performance Requirements, the first two levels of which are given in Table 1. A complete tabulation would show further decomposition. The system *IFMS* is required to operate to standards of efficiency as judged by the criteria in SYSTEM OPERATION. The goals and requirements of the farmer and general public (environmental concerns and the need for food and fiber) are considered in the QUALITY of FARM PLANS set of requirements. The final set of requirements, RESEARCH PRODUCTIVITY, was imposed by ARS to ensure the system would be consistent with ARS's mission and objectives as a research agency. Each FoM was assigned weight and parameter values in accordance with the customers' preferences, determined in interviews, using the Standard Scoring Functions (SSF) methodology of (Wymore, 1993).

FUNCTIONAL DESIGN

The overall **functionality** of the system IFMS can be **described as shown in Fig_** 1, a simplified functional diagram. Demands and resources are sent to **subsystem ACCEPT. Demands can range from farmers' requests for** farm management plans which include site/farmer specific data, to new environmental laws that impact farm management. Resources are transferred to subsystem FUND. Demands are sent to subsystem INTEGRATE where the existing body of knowledge is evaluated and integrated for the best response to the demand in terms of agricultural, environmental, economic and social conditions. The integration process may range from a committee reaching consensus to the use of sophisiticated decision support software. The outputs from INTEGRATE are PLANS and DATA GAPS. PLANS can take two forms. Recommended Plans or Interim Plans. If there is sufficient, validated information to deliver Recommended Plans at a risk level acceptable to the farmer, the Plans are generated and delivered. If there is no fully acceptable Plan available based on current information, INTEGRATE will generate an Interim Plan with its limitations and uncertainties clearly stated. At the same time INTEGRATE will **output the** DATA GAP(s) that must be filled before a Recommended Plan can be generated to replace tk Interim Plan.

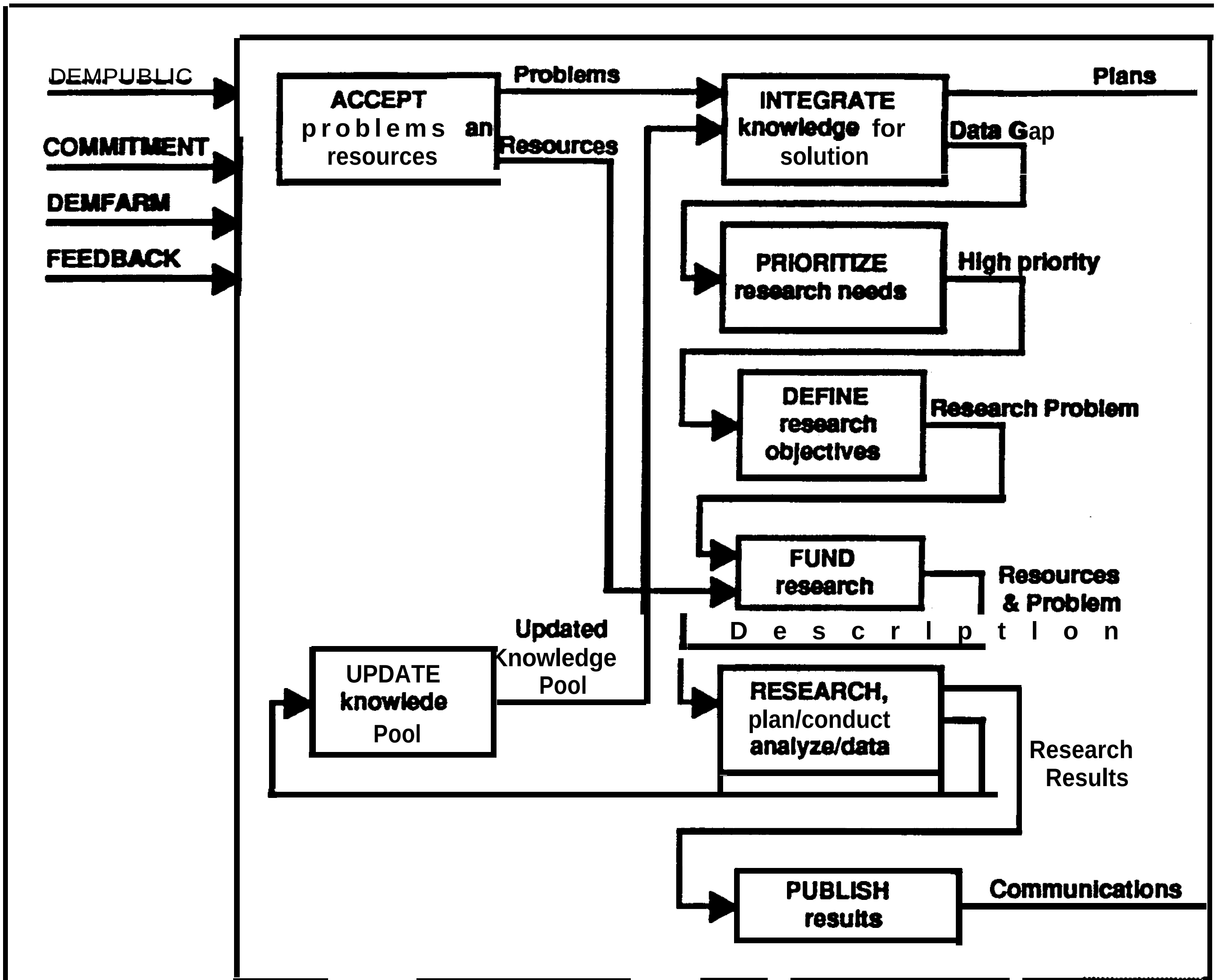

FIGURE 1. Functional Diagram of the Integrated Farm Management System.

The DATA GAPS are input to subsystem PRIORITIZE which outputs a prioritized list of research needs. The top ibm on the list is passed to subsystem DEFINE. DEFINE generates a clear statement of the research problems to be addressed including criteria to be used to judge the completeness of the research program, the resources needed for the research, and the tests the research results must pass. The complete description of the research problem, as generated by DEFINE, is then sent to subsystem FUND. FUND determines who will do the research and transfers resources and the research problem statement into subsystem RESEARCH. The RESEARCH subsystem plans and conducts research and analyzes the results. The results from the RESEARCH subsystem are passed to the PUBLISH subsystem and the UPDATE subsystem. UPDATE accepts the research results and incorporates the new knowledge into the whole body of existing knowledge for farm management. UPDATE passes the enhanced pool of information to INTEGRATE. Subsystem PUBLISH accepts research results and produces publications. These publications may thake the form of refereed journal articles, trade journals, technical reports, and software. Numerous forward and backward feeds between subsystems also exist.

CONCEPT DEVELOPMENT

Four physical concepts were developed that met the functional design. The assignment of physical

FUNCTIONS	COMPONENTS			
	PANELS	GRANTS	CRIS	CONTRACTS
ACCEPT	Director, NSTL	Director, NSTL	Systems SY	Director, NSTL
INTEGRATE	Ad-hoc Committee	Ad-hoc Committee	Systems SY & Info Specialist	Systems SY & Info Specialist
PRIORITIZE	Ad-hoc Committee	Ad-hoc Committee	Systems SY & Ad-hoc Committee	Director, NSTL & Ad-hoc Committee
DEFINE	Ad-hoc Committee	Ad-hoc Committee	Systems SY	Systems SY
FUND	Voluntary SYs	Ad-hoc Committee	Systems SY & Cooperators	Director, NSTL (IFMS$)
RESEARCH	Voluntary SYs	Grant Principal Investigators	Systems SY & Cooperators	Contract SYs & Systems SY
PUBLISH	Voluntary SYs	Grant Principal Investigators	Systems SY & Cooperators	Systems SY & Contract SY
UPDATE	Ad-hoc Committee	Ad-hoc Committee	Computer Spec & Info Spec	Computer Spec & Info Spec

TABLE 2. Assignment of Components to System Functions for Each Concept.

components to functions is shown in Table 2. Concept PANELS provides for the Director, National Soii Tilth Lab (NSTL), Ames, IA to coordinate the voluntary cooperation of existing ARS, university, and other research organizations to develop validated Farm Management plans for the Walnut Creek Watershed. This concept requires no new funding, however it should be recognized that "voluntary" participation diverts a scientist's time and resources away from other research areas and does incur a "cost". Although the advantage of this system is that it costs very little in new money, the lack of monetary incentive to offset direct research costs is a great disadvantage. PANELS allows a large degree of input from the immediate farming axnmunity and agricultural support agencies, both commercial and private. This has the potential of stimulating outside funding resources for projects with local interests. PANELS relies upon local and available scientific knowledge to deliver answers to concerns without the necessity of cresting, building or maintaining permanent database structures. The system relies on the desire of the researcher to focus on locally relevant issues or to develop potentially beneficial relationships with senior scientists on the Ad-hoc Committee. Efficiency of the system will depend in large part on the interest and schedules of the Ad-hoc Committee members.

Tbe Primary difference between GRANTS and PANELS is that a source of "new" money provides an incentive for scientists to implement the research function A functional diagram of the RESEARCH subsystem under GRANTS would differ from that under PANELS primarily in containing a substantial function relating to solicitation of research proposals and a competitive review function for selecting winning proposals. The PANELS research subsystem would function mainly to convince targeted researchers on the priority and potential professional payoffs of working in the context of IFMS. Since scientists from many disciplines associated with ARS and Iowa State University are familiar with the grant process, response to each Request for Proposals (RFP) should be more than adequate. One of the weakness is that grant programs are often used to sustain on-going research programs. Even when RFPs are written with very specific requirements, they are still subject to individual interpretation and thus proposed activities may or may not meet the needs for new knowledge that address real farmer demands and problems, -The speed with which routine requests could be processed would be slow due to tbe need for committee meetings. The cost of GRANTS is reduced since many of the functions in GRANTS can be performed by Ad-hoc Committees of persons currently associated with projects at the Walnut Creek Watershed (Table 3). Realistically, each research project that is funeded through this process should have approximately $20K to $40K per year to provide sufficient resources to conduct meaningful research.

In contrast to PANELS and GRANTS, the CRIS concept relies on permanently funded, formally managed research with true accountability for results and is similar to the present ARS research management system. A Research Scientist (SY) with technical support would develop and maintain a database of existing, validated farm management options which is accessed by decision support software to generate a

Management	GRANTS
Overhead	$6,000
	(3% of research funds
Integration	
No costs	so
Research	
Funds available for grant research per year	**$200,000**
TOTAL	
One time expenses	**$0**
Annual Budget	**$206,000**

TABLE 3. Estimated Costs of GRANTS.

specific, integrated farm management PLAN for a farm in the Walnut Creek Watershed near Ames, IA. This system relies heavily upon cooperative research with other scientists from both the public and private sectors to develop new information for updating the database. The system is managed in-house under the supervision of the Director, NSTL. It identifies and addresses information gaps through information retrieval, networking with interdisciplinary units, and its own research activities. Research conducted locally is expected to result in a high degree of relevance to the information needs for farm management in the Walnut Creek Watershed. Community involvement in the priority setting process is expected to increase community acceptance and ownership of the project. The computerized database, once developed, is expected to give quick, high quality responses to routine requests for farm plans. Cooperation is expected to be good based on a strong history of good cooperation between ARS and Iowa State University and Extension, but there is no inducement for cooperation such as the funding provisions found in GRANTS and CONTRACTS. The performance of the system will be limited by the'level of voluntary cooperation obtained and the workload of the SY. Costs of this system would include salaries and benefits of the researcher and technicians, costs for initial equipment, and operational costs to include those needed to conduct field-scale research projects. The total sum of non-recurring costs for computers, workstations and software to support the development of a data base and the initiation of the decision support system development is estimated to be $35,000. Total recurring costs would be $391,000 per annum (Table 4).

Concept CONTRACTS is very similar to CRIS. The major difference between the two concepts is that the system manager will award temporary funds on a **contract basis to ARS** scientists to perform specific research activities and deliver agreed upon products at the conclusion of the contract rather than assign all of the RESEARCH function **to** the Systems Engineer/Scientist. Research areas to be funded will be selected from a prioritized list of problems resulting from new legislation, identification of critical research gaps, demands from consumers and similar sources of input. Funds for this research will be assigned by the system manager and released to a research unit for a specified period of time. Periodic review will assure the money is being used to perform the research agreed upon in the contract. The computerized database and decision support system is expected to provide quick, **high qualityresponses to requests for solutions to farm** management problems for which **a** solution already exists in the database. For thsoe requests that require additional research, CONTRACTS provides

Management	CRIS
Overhead funds per year	**$6,000**
Integration	
Systems Scientist per year	**$55,000**
Information Specialist per year	**$40,000**
Computer Specialist per year	**$40,000**
Supplies and Equipment per year	**$50,000**
Computer Workstations, Laser printer	**$20,000 (One time)**
Temporary labor to do initial data entry	**$15,000** (One time)
Research	
Funds available for research activities per year	**$200.000**
TOTAL	
One time expenses	**$35,000**
Annual Budget	**$391,000**

TABLE 4. Estimated Costs of CRIS.

greater flexibility to fund specific research programs than hiring permanent positions for component research while at the same time having a higher probability of generating the necessary information than a grants program. The level of funding will determine how many research programs can be ongoing at one time. Local management of the system should insure a high degree of availability. Community involvement in the priority setting process is expected to increase community acceptance and ownership of the project. Cooperation with other government agencies, the university, farmers, and private industry is expected to be high based on the level of cooperation observed in current programs at the Ames, Iowa location. One weakness may be resistance on the part of the researchers to accept the more structured contract approach to doing research. Another might be the ability of the local system manager to objectively consider contract bids from ARS scientists located in other areas. Costs of this system would be the same as the costs for CRIS (Table 4).

CONCEPT COMPARISON

Input trajectories for the evaluation of the concepts consist of situations that may occur over a time interval of three years. Three situations are considered for the evaluation of the four concepts 1) STATUS QUO. 2) ENVIRONMENT CHANGE, and 3) MARKETING CHANGE. The STATUS QUO situation represents the current states in ARS. There is little opportunity for new money and resources to be devoted for IFMS: a hiring freeze exists and personnel ceilings are limiting; there are restrictions on personnel relocations. The ENVIRONMENT CHANGE situation occurs when an important environmental problem is identified. This could be at a moderate level or a high level; for example, a recommendation to reduce total pesticide usage. or a more serious National concern, such as a regulatory mandate prohibiting use of a specific pesticide. The situation would make new "directed" monies available and increase the interest in IFMS. The regulatory restrictions would require changes in farm management. In this situation there may be some flexibility in hiring and relocation restrictions. In the MARKETING CHANGE situation, a marketing change is hypothesized. For example. foreign comepetition might lower or raise prices significantly or foreign market demands might require changes in farm management practices to reduce pesticide residues or improve quality. Such changes would cause pressure on farmers at the local level. There might be increases in funding from specific commodity groups and a local increase in interest in IFMS.

The first input trajectory (SCENARIO 1) projects the STATUS QUO exists for the next thee years. The second input trajectory (SCENARIO 2) has STATUS QUO for one year, followed by two years of ENVIRONMENT CHANGE, This is a slightly more volatile trajectory and introduced to measure the expected flexibility of the proposed systems to change. The final input trajectory (SCENARIO 3) considers a year of STATUS QUO, a year of ENVIRONMENT CHANGE, and a year of both ENVIRONMENT and MARKETING CHANGE. This secenario contains more volatility than Scenario 2. For the purposes of evaluation all input trajectories are equally weighted. With limited systems engineering resources 'it was not feasible to develop detailed models of the concepts. Instead, rough conceptual models have been developed, scoring functions and weights have been assigned to each FoM and best-guess evaluations were conducted by a panel. Many of the arguments that justify and support the evaluations have been presented in the description of the strengths and weaknesses of the alternative concepts. On the bask of these evaluations for performance, CONTRACTS ranked highest with an overall score of 05255 (Table 5). PANELS ranked lowest, indicating that this concept would likely be the least effective of the four concept alternatives in producing the desired objectives of IFMS based upon performance alone.

	PANELS	GRANTS	CRIS	CONTRACTS
SCENARIO 1	0.2062	0.3288	0.4316	0.5162
SCENARIO 2	0.1921	03162	0.4311	0.5363
SCENARIO 3	0.1865	0.3358	0.4370	0.5239
OVERALL	0.1949	0.3269	0.4332	0.5255

TABLE 5. Evaluatlons ofeth Performance of the Fo r Concepts.

TRADEOFF ANALYSIS

The Tradeoff Analysis was conducted tocalculatethe tradeoff between performance and cost. Costs of the individual concepts have been estimated in Tables 3 and 4. Formulae for tradeoff between performance and cost can be simple or complex based upon the client's interests. For simplicity. a cost/benefit ratio analysis was considered herein. In otherwords, how much performance could be derived for each dollar spent? For the purposes of this estimation, the total cost of each concept is based upon the "one-time" expense for startup plus three years' annual budget. PANELS gives the most performance per cost despite its low performance estimates because no "new" cost is assessed. The risk of choosing this concept must be considered. It has been noted already that because money is not provided. the degree of control is low and dependent upon local interests and competition with other priorities. In addition, PANELS relies upon research being conducted though the redirection of resources by principal investigations. In fairness, these resources may have to be considered in a realistic comparison of benefit ratio: however, the customers did not want to include the cost of these resources in the comparison at this time. Certainly, cooperators within the agency would be, in fact, making a contribution to the IFMS effort. On an administrative level. this type of cooperation may be looked upon as a fine-tuning or an integration of present efforts. Under the present limited budget situation of ARS and the low importance being placed on lFMS. PANELS would seem to be the most recommended feasible, achievable. buildable, and implementable systems design concept.

SENSITIMTY ANALYSIS

Sensitivity analysis was conducted to determine which Performance FoMs have the greatest effect at overall performance. This was done by increasing tk **hypothetical performance for each** FoM by 5% over its baseline value and determining the impact on the overall system perfamance score. The system was most sensitive to the ENVIRONMENTAL FoM followed by the ECONOMIC and SOCIAL FoMs. Based on tk weighting factors alone given in Table 1, it would be expected that the RESEARCH ACCOMPLISHMENT FoM would have the greatest influence. This was not the case. **however. since the** SSF **assigned** to RESEARCH ACCOMPLISHMENT was a linear function. and the SSF 'assigned to the ENVIRONMENT AL. ECONOMIC, and SOCIAL FoMs was a sigmoid curve with a very steep slope at the midpoint. Thus a one unit increase in performance for ENVIRONMENT caused a much larger increase in the performance score for ENVIRONMENT than a one **unit increase in** RESEARCH ACCOMPLISHMENT caused in the relative score for RESEARCH ACCOMPLISHMENT. Within the category of RESEARCH PRODUCTIVITY, the RESEARCH ACCOMPLISHMENT as measured by publication and software development, was the most important factor. FoMs within the SYSTEMS OPERATION category were relatively balanced. This analysis indicated that systems functions that impact the farm PLAN QUALITY in a positive **manner would produce the** greatest change in overall evaluation of a design. In other words. resources aimed at improving PLAN QUALITY would have the greatest positive impact on overall system performance.

CONCLUSION

The development of a comprehensive IFMS program is an extensive and complex task. It spans agencies within USDA, EPA, and enterprises both public and private. IFMS is an interdisciplinary effort that requires biological, physic4 and social sciences. In order to achieve the goal of producing a system design for ARS within the context of its research framework, only the top level design has been developed for the purpose of selecting among alternative concepts. The alternatives suggested are not new. By mandate, the concepts were directed to fit into the existing ARS structure. Exploration of the best design was complicated by the fact that resource allocations were not specified. Just as it would be easier to design three different concepts of race car given a specific cost estimate than to design three concepts ranging in price from $10 to $100,000: so, too, was the IFMS assignment complicated by the lack of solid information on resource availability. The results of the estimates of performance reflect this limitation: performance is a function of cost. The four concepts presented, vary in their cost and the level of performance available for that cost. Regardless of the **limitations of the process as** it has been **presented, this systems engineering appkation has resulted in a strong documentable basis for the development and implementation of several design concepts for IFMS, any of which are buildable within present technologies. Additionally, this pilot project confirmed the usefulness of Systems Engineering in agricultural research.**

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BIOGRAPHIES

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