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Systems Studies and Modeling of Advanced Life Support Systems

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Abstract: Advanced Life Support Systems (ALSS) are being studied to support human life during long-duration space missions. ALSS can be categorized into four subsystems: Crew, Biomass Production, Food Processing and Nutrition, Waste Processing and Resource Recovery. The System Studies and Modeling (SSM) team of New Jersey-NASA Specialized Center of Research and Training (NJ-NSCORT) has facilitated and conducted analyses of ALSS to address systems level issues. The underlying concept of the SSM work is to enable the effective utilization of information to aid in planning, analysis, design, management, and operation of ALSS and their components. Analytical tools and computer models for ALSS analyses have been developed and implemented for value-added information processing. The results of analyses have been delivered through the internet for effective communication within the advanced life support (ALS) community.

Several modeling paradigms have been explored by developing tools for use in systems analysis. They include object-oriented approach for top-level models, procedural approach for process-level models, and application of commercially available modeling tools such as MATLAB^{R}/Simulink^{R}. Every paradigm has its particular applicability for the purpose of modeling work. An overview is presented of the systems studies and modeling work conducted by the NJ-NSCORT SSM team in its efforts to provide systems analysis capabilities to the ALS community. The experience gained and the analytical tools developed from this work can be extended to solving problems encountered in general agriculture.

Keywords: System studies, Modeling, Advanced life support systems, Top-level modeling

Introduction

In order to support human life, we need access to food, water, oxygen, and shelter. For a long-duration manned space mission, as mission duration increases (e.g., up to three years for a Mars mission), the use of regenerative life support systems becomes more economical and tenable compared to storing or resupplying materials. To investigate regenerative life support systems, tightly controlled and closed loop systems called Advanced Life Support Systems (ALSS) have been developed to produce food, purify water, regenerate oxygen and nutrients, and remove undesirable contaminants (Fig. 1). They can include the subsystems Crew, Biomass Production (BP), Food Processing and Nutrition (FPN), Waste Processing and Resource Recovery (WPRR).

There are four research teams at the New Jersey-NASA Specialized Center of Research and Training (NJ-NSCORT), including Biomass Production, Food Processing and Nutrition, Waste Processing and Resource Recovery, and System Studies and Modeling (SSM), conducting a number of projects that address specific problems concerning the design of ALSS. Information and knowledge from different research teams are needed for planning, analysis, design, management, and operation of ALSS and their components. Not only the quantity and quality of information, but also the methods of information usage

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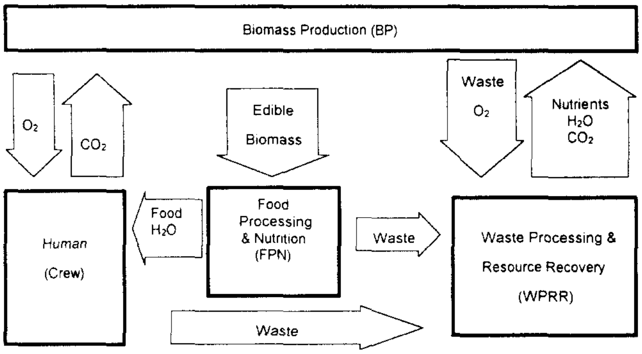


Fig. 1 A schematic diagram of an Advanced Life Support System including the subsystems Crew, Biomass Production (BP), Food Processing and Nutrition (FPN), and Waste Processing and Resource Recovery (WPRR).

are important to enhance the research productivity in the Advanced Life Support (ALS) community. Many valuable research results and data have been obtained from research into various ALSS, their components and processes. The variety of information is as diverse as its sources and sometimes it is dissociated from each other. Thus, one of the goals of the NJ-NSCORT SSM team was to establish the effective gathering, storing, processing, and presentation of information and knowledge. For ALSS analyses, analytical tools and computer models have been developed and implemented for value-added information processing with scientific methods of information synthesis and application. The results of the analyses have been available through the internet environment for effective communication within the ALS community.

Before a long-duration manned space mission can be under taken, complete mission scenarios need to be evaluated using full-scale ALSS occupied by humans. Therefore, NASA has developed a high-fidelity test facility capable of evaluating full-scale Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) with human crews for long durations (Fortson and Castillo, 1997; Kirby et al., 1997). This facility will provide NASA with a test bed capable of continued, and extended bioregenerative life support technology development; it can serve as a focal point for other disciplines to conduct research, and it can be used to develop supporting technologies, techniques, and procedures pertinent to future planetary missions via cooperative and collaborative experimentation and testing. To reflect the anticipated design of the BIO-Plex and its advanced technologies and science, more functional mathematical models need to be developed as researchers generate new knowledge or as ALSS perspectives change. Thus, the NJ-NSCORT SSM team has developed models to analyze the ALSS and to calculate whether a given system is capable of completing a mission.

The development of an ALSS is an interactive process involving the evaluation of technologies, systems analysis and design, and testing of system components. To do this efficiently, it is necessary to incorporate system analysis models into the ALSS technology development process. An Information Flow Analysis (IFA) was developed to produce data regarding ALSS research projects on a real-time basis on the internet. This data compares and contrasts research activities, produces quantitative data reflecting project interactions, completeness, functionality, and comprehensiveness. Also provided in the IFA is a function for the real-time monitoring of the alignment among projects and roadmaps. The utility of the IFA is demonstrated by inputting information from the NJ-NSCORT research community (Rodriguez, 1999) and the Lunar Mars Life Support Test Project (Phase I III) (Rodriguez et al., 1999a). The use of the IFA resulted in a better understanding of ALSS, and enhanced the related technology development processes. The design of the IFA is general enough to be able to accept and process information from any ALSS research project.

An object-oriented approach has been used to develop top-level models for subsystems of ALSS. Top-level models for four subsystems in ALSS, namely Biomass Production model (Fleisher et al., 1999), Waste Process and Resource Recovery model (Rodriguez et al., 1999b), Crew model (Goudarzi and Ting, 1999), and Food Processing and Nutrition model (Hsiang et al., 2000), have been developed. One overall top-level model of an ALSS is being developed based on all the subsystem top-level models. A parallel effort is underway to further the development of the BP model. This particular study involves the evaluation of mechanization, automation, and robotics systems (MARS) for various biomass production scenarios (Kang et al., 2000).

In a parallel activity involving object-oriented modeling for an ALSS, MATLAB®/Simulink® was used to develop modules for indirect validation of the object-oriented models. The system analysis provided by the BIO-Plex model results in recommendations for the component processes of ALSS. For example, a detailed composting module was integrated in an existing dynamic BIO-Plex systems model, written in MATLAB®/Simulink® (Finn, 1999), to calculate composting reactor sizes and mass flows based on various waste input scenarios.

The NJ-NSCORT SSM team provided an internet site for not only an information exchange, but also as a test site for developed models. Several models developed so far have been tested and used by ALS community members. This paper describes an overview of the systems studies and modeling work conducted by the NJ-NSCORT SSM team in its efforts to provide systems analysis capabilities to the ALS community.

Methods

1. Establish Communication

As one of the essential tools needed for information integration, a common communication platform was established to facilitate the flows of information from various sources and to appropriate users. The distributable and multiplatform environment of the internet was utilized as a test bed for this project. The World Wide Web (WWW) was used as the common communication channel for the ALS research community to gather project information of each research discipline, store the information in a database (information modules), present the gathered data, provide a discuss forum, and process the information (functional modules).

An interactive web server has been established to enable online information gathering, and to communicate with the ALS research community. For handling dynamic page information (e.g., texts and tables), the developed information system uses a database management system with a web application development tool (Cold Fusion, Allaire Corp., Cambridge, MA), to gather and exchange information among ALS researchers and other visitors who are interested in ALS research (Fig. 2).

Several software programs were installed on a dedicated web server (http://nj-nscort.rutgers.edu) to handle information from the ALS research community, and to execute several models developed by the SSM team. A software called Website Professional 1.1 (O'Reilly & Associates, Sebastopol, CA) was used to operate the web server. Cold Fusion Pro 2.0 and Microsoft Access (Microsoft Office 97, Microsoft Corp., Redmond, WA) were used for database management. Because Adobe Portable Document File (PDF) can be used on any platform with Adobe Acrobat Reader available for free from Adobe Systems Inc. (San Jose, CA), Adobe Acrobat 4.05 (Adobe Systems Inc., San Jose, CA) was installed to create PDF files. For the purpose of using internet capable, object-oriented programs, Symantec's VisualCafé™ 4.0 Expert Edition (Cupertino, CA), Sybase's Structured Query Language Anywhere 5.0 (Emeryville, CA), dbANYWHERE 1.1a (Symantec Corp., Cupertino, CA), Rational Rose 98 (Rational Software Corp., Cupertino, CA), and Visual Studio 6 (Microsoft Corp., Redmond, WA) were installed.

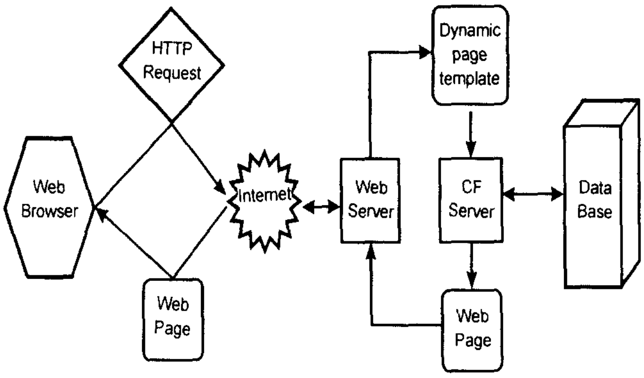


Fig. 2 Schematic diagram of a web based information system developed to establish communication among ALS researchers (Ting et al., 1997).

By using the interactive Web forms, a user enters information into a relational database, which can be organized as tables in Microsoft Access. An Open Database Connectivity (ODBC) driver in Microsoft Access is used to establish a communication interface between the information database and the Cold Fusion Web application program. If a user wishes to look at specific information, dynamic-page templates, including both Hypertext Markup Language (HTML) and the Cold Fusion Markup Language (CFML), are preprocessed by the Cold Fusion application server, resulting in the generation of an interactive HTML page that is then sent to the client's browser.

2. System Studies and Modeling

(1) Information Flow Analysis (IFA)

By utilizing Object-oriented Analysis (OOA) techniques (Booch, 1994), two abstractions were developed for systems analysis. One represents the ALSS goals and the other describes the tools utilized to achieve these goals. It is possible to perform systems analyses utilizing these abstractions, and afterwards distribute the results to researchers via the internet by using Java internet technology. Furthermore, it is possible to display the processed information showing the achievements of ALS goals, the contributions of the research, the integration of ALS projects, and the progress of research projects. The utility of the IFA was demonstrated by inputting information from the NJ-NSCORT research community, and Lunar Mars Life Support Test Project (Phase I - III). (Rodriguez, 1999; Rodriguez et al., 1999a)

(2) Top-Level Modeling of ALSS using Object-oriented Approach

The developed object-oriented models followed the techniques of object-oriented analysis (OOA), object-oriented design (OOD), and object-oriented programming (OOP). The OOA (Booch, 1994) has been applied to extract classes and objects from ALSS components. A class is a generic template for a set of objects with similar features (i.e., attributes). The visual object modeling development tool, called Rational Rose, was used to design a global ALSS class library (Chao et al, 1997). The OOD for ALSS was constructed using a two-dimensional matrix. For example, using the BP model, automation, culture, and environment parameters can be represented by row vectors, and ALS subsystems by column vectors. By using constructed OOD, OOP was performed with the help of several software programs developed by Symantec to create and modify the BP model. Symantec's VisualCafé^{TM} 4.0 (Expert Edition), with its database access capability, was used to develop the model source code. Symantec's VisualCafé^{TM} uses the Java^{TM} programming language to represent the object-oriented concept. Sybase's SQL Anywhere 5.0 was utilized for the development of the model's database. The class/object database contains specific information on variables which represent each class, and the detailed values which define each object used in the simulation. The scenario database stores variables which describe the different mission scenarios. Class/object and scenario data interfaces were developed to access the class/object and scenario databases. Symantec's dbANYWHERE server 1.1a was used to create a real-time platform, which independently links between a user running the model and the databases for that model. A JavaChart class library from Visual Engineering, Inc. (Los Altos, CA) is utilized for graph generation of the simulation results.

(3) An Example of Top-Level Modeling of ALSS using MATLAB^{R}/Simulink^{R}

A detailed composting module as part of the existing BIO-Plex model was developed to calculate composting reactor size and mass flows. A first order kinetic model (Marugg et al., 1993) was used to calculate the rate of conversion of mass in the composting process. The transient waste mass (moles) in the composter was obtained from the equilibrium mass of the compost mixture, a degradable factor, the reaction rate, and the initial dry mass of the waste. The degradable factor is the fraction that is expected to be readily degraded during composting. Its values range from 0 (none degraded) to 1 (complete degradation).

A stoichiometric equation was used to calculate human waste generated by the crewmembers based on crew metabolism (Volk and Rummel, 1987). Human waste was assumed to be 80% urine solids, 17% feces solids, and 3% sweat solids (mole percentage). All waste materials considered are solid phase and include: human waste (urine, feces, and sweat solids), food preparation waste (protein, carbohydrate, and fat), inedible plant matter (protein, cellulose and lignin), and paper trash. Initial data for the required amount of food for a crew, and the amount of paper trash generated were obtained from the ALS Requirements Definition and Design Consideration Document (Lange and Lin, 1998). The amounts of food preparation and inedible biomass wastes were taken from a paper by Wydeven et al. (1989). The ratios of protein, carbohydrate, and fat from food preparation waste were assumed to be the same as those for the food. The inedible biomass mix was assumed to be made up of 10% protein, 60% cellulose, and 30% lignin (weight percentage) for each crop. Based on the above waste input scenario, composting reactor size and mass flows were determined using the composting module within the BIO-Plex model.

Results and Discussion

1. Establish Communication

A basic framework for an interactive web site has been completed and implemented. The NJ-NSCORT website (front page, Fig. 3) includes an overview, research, applications, training, facilities, documents, and news information. For example, the listed documents include continuous updates of monthly reports of the NJ-NSCORT projects, and weekly reports from other NASA research centers. Informational modules and the associated functional modules such as project information, project report summaries, and discussion forums have been actively used by NJ-NSCORT members and the larger ALS community. Among several options, the "News Group" function has been used extensively to carry out lively discussions among members of the ALS community. It was considered a pre-meeting discussion, and as much contributed to the success of the ALSS Workshop held in Houston in March 1998. The NJ-NSCORT website has been designated as the official communication website for the Systems Integration, Modeling, and Analysis (SIMA) of NASA's Advanced Life Support Program. It is also an official website of the 4th International Conference on Life Support and Biosphere Science, Baltimore Marriott, Inner Harbor, Baltimore, Maryland, August 6-9, 2000. General information, call for abstracts, registration, hotel, entertainment, and travel information regarding this conference was provided to anyone who wished to attend.

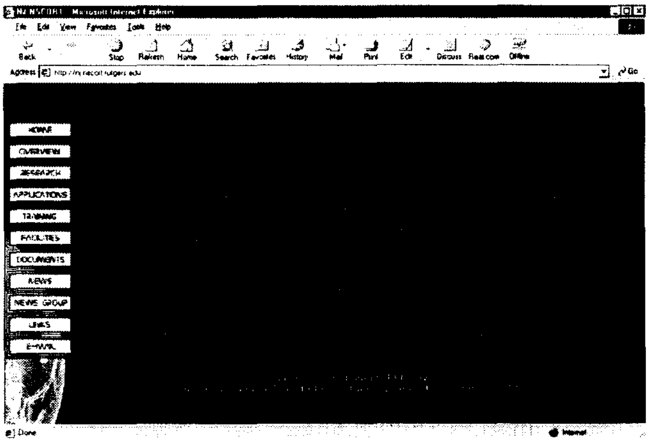


Fig. 3 Front page of NJ-NSCORT website with various functions: http://nj-nscort.rutgers.edu

The NJ-NSCORT web site is capable of real-time collection, processing, and displaying of information. It also provides document uploading, downloading, and browsing capabilities. The development of this web site is continuing with several internet capable Java^{TM} base software tools. More informational modules and functional modules will be added in an effort to provide an effective platform for concurrent science and engineering in supports of ALS developments.

2. System Studies and Modeling

(1) Information Flow Analysis (IFA)

Four metrics (comprehensiveness/redundancy, completeness, functionality, and integratibility) have been developed as part of the IFA technique to assess the state of ALSS research. The metrics were calculated based on information regarding project activity, research goals, and project roadmaps. A database housing this information was accessed by the software; and the calculation of these metrics was performed by computer algorithm. As long as the database was maintained regularly, relevant real time information was generated when the metric values were calculated. The IFA has effectively provided value-added information regarding the status of ALSS research within the NJ-NSCORT and the Lunar Mars Life Support Test Project (Phase I III) (Fig. 4).

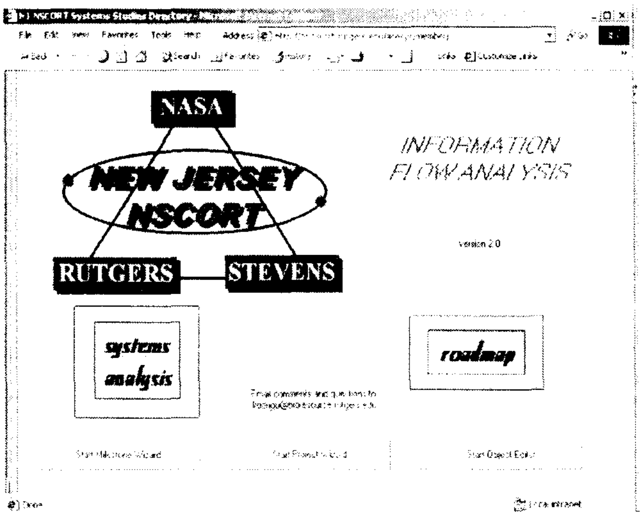


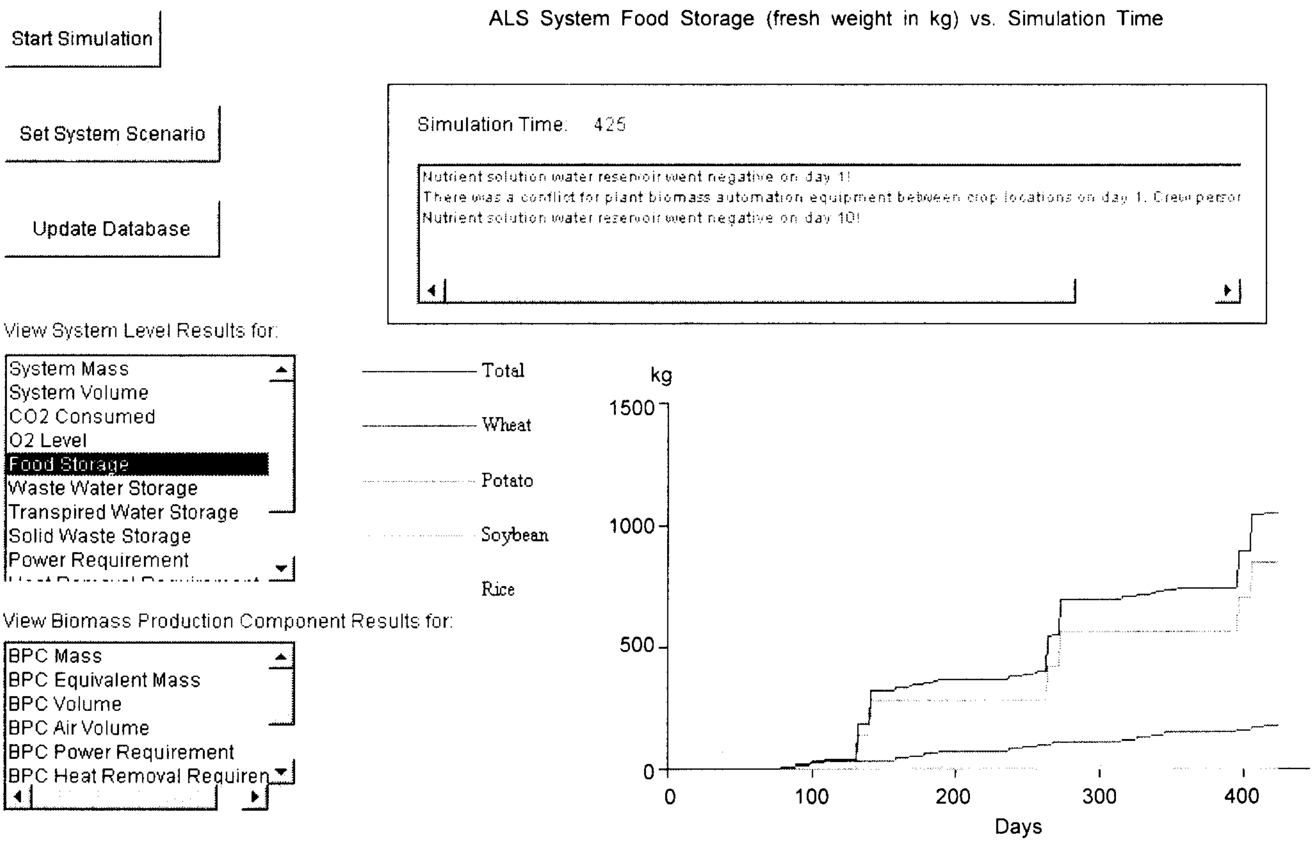
Fig. 4 Front page of the Information Flow Analysis (IFA) tool developed by Rodriguez (1999).

Metrics and other system analyses included in the IFA were interpreted individually or combined to assess project information and research requirements. Trends of metrics over time offered another perspective on the status of the research. The methodology employed in the development of the IFA technique is applicable in other multidisciplinary agricultural and biosystems engineering research fields, multinational corporations, and government institutions.

(2) Top-Level Modeling of ALSS using Object-oriented Approach

Currently, the BP model is the most complete of all the concurrent modeling efforts (Fleisher et al., 1999). The BP model focuses on the growth of plant matter and its interaction with the surrounding environment. Gas exchange, water uptake, power requirements, heating and cooling requirements, crew time requirements, and equivalent system mass can be determined for a given system and mission scenario. In Fig. 5, two list boxes display the top-level variables for an ALSS mission including the BP component. The three gray colored buttons on the top left of the screen provide access to the database via scenario or class/object data interfaces, or start the simulation utilizing current data. This BP model can be linked to connecting model inputs for CO_2 and H_2O to Crew and WPRR component outputs, respectively. Outputs from the BP model, including O_2, food (edible biomass) storage, solid waste (inedible biomass) storage, and transpired water would connect to Crew, FPN, and WPRR component inputs. The inter-connecting tunnel between ALS components would serve as buffer storage space (Fig. 1).

The WPRR model focuses on the handling of wastes within ALSS. An air revitalization system, a water processing system, and a solid waste processing system are included in the WPRR model (Rodriguez et al., 1999b). The crew model was designed and implemented to examine the physical needs of crewmembers with respect to the effects of varying mission lengths, habitats, and specific human characteristics (Goudarzi and Ting, 1999). The FPN model includes a routine to determine if the nutritional needs of the crew are met (Hsiang et al., 2000). As these top-level sub-models are developed and integrated, a useful tool for studying robustness and management of ALSS will be available. These models



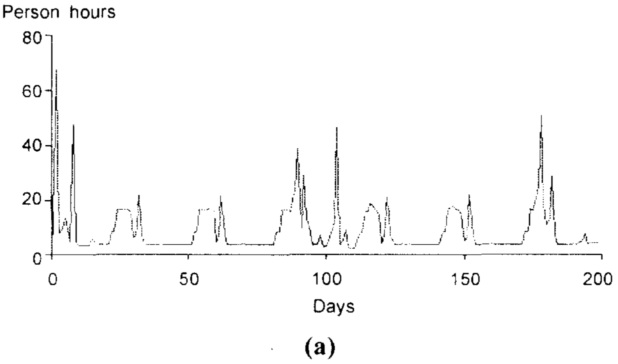
Simulation Time: 425

Nutrient solution water reservoir went negative on day 1!
There was a conflict for plant biomass automation equipment between crop locations on day 1. Crew persor
Nutrient solution water reservoir went negative on day 10!

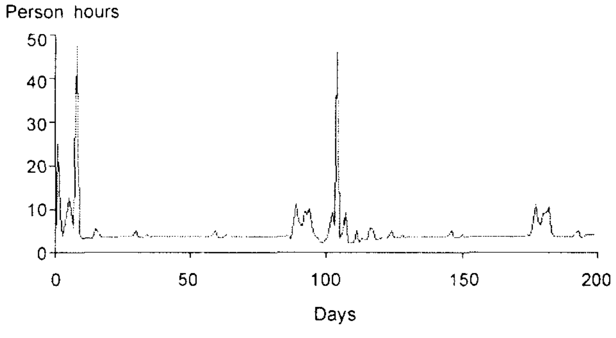
Fig. 5 The Biomass Production Component of an ALSS. Graph shows the amounts of stored biomass. (Fleisher et al., 1999).

can be expanded to study the agricultural production, food processing, and waste processing systems in agricultural and biosystems engineering research fields.

The existing object-oriented BP model (Fleisher et al., 1999) was modified by updating the crop production data. The model was expanded to incorporate various types of mechanized equipment, automated machines, and/or robots. The model can simulate different combinations of crop mix and scheduling, cultural tasks, production space layout and materials flow, and crew and machine interactions to investigate crew time requirements and equivalent system mass (Fig. 6). The outcome of the simulations will be useful for developing recommendations regarding the amount of automation needed for biomass production. The development of automation for plant materials handling in ALSS can be applied in the bedding plant and cell/tissue culture industries and in automated greenhouse operations.



(a)



(b)

Fig. 6 Side-by-side comparison of crew time requirements for an example biomass production scenario with and without automation: (a) Crew time requirements resulting from the BP model simulation without automation, (b) Crew time requirements resulting from the BP model simulation with automation (Kang et al., 2000).

(3) An Example of Top-Level Modeling of ALSS using MATLAB®/Simulink®

Solid wastes resulting from biomass production, food processing, and crew activities are treated in the waste processing and resource recovery (composting) subsystem. Oxygen consumption, carbon dioxide production, and water use/generation from composting was less than 50% when compared with incineration. The specified waste retention time was 42 days. Because of the balance between finished compost and daily-added fresh waste, waste accumulation remained at a constant level in the composting reactor. Because of low degradability, proportions of the paper trash, cellulose, and lignin in the inedible biomass slowly increased in relation to the initial proportions in the waste feedstock (Kang et al., 1999).

The developed composting simulation model has been used to evaluate the waste generation process from the biomass production, food processing, and crew activities. This model can determine the amount of waste production, recovered resources, and the resulting process residues (Fig. 7).

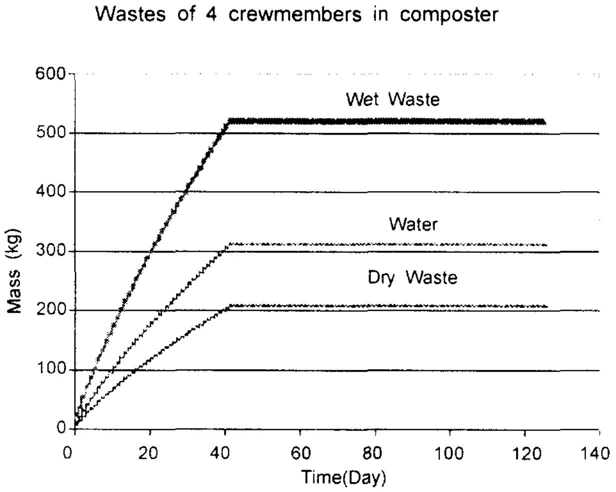


Fig. 7 Total wet, dry, and water masses in a composting reactor (number of Crew members = 4) (Kang et al., 1999).

The developed composting model can individually analyze a wide variety of biologically dissimilar compounds to account for their susceptibility to degradation. This is valuable because the waste producing components need to be highly defined in closed ALSS. Composting reactor sizes and masses can be calculated based on various input scenarios, including various levels of food production (i.e., inedible biomass formation) and specific waste production (e.g., paper trash). This model can be used to analyze and design composting systems for non-ALSS applications.

The experiences gained and the analytical tools developed from this research conducted by the SSM team of the NJ-NSCORT, may be extended to solving problems encountered in general agriculture. For example, the knowledge gained from ALSS biomass production can be used by growers in their greenhouses or in the open-field. Some of the developed models can be used to analyze biomass production, food processing, and waste processing in non-ALSS applications. The developed systems studies and modeling techniques can be used by agricultural and biosystems engineers to understand diverse agricultural, environmental, biological and ecological systems on Earth.

Conclusions

1. The NJ-NSCORT System Studies and Modeling (SSM) team has provided a way to facilitate communication and to share technical information among ALS members.
2. The Information Flow Analysis (IFA) has provided a real-time systematic analysis on the coordination of ALS research activities directly to researchers in the ALS community by using the latest internet technology.
3. Top-level modeling work has been focused on the development of an integrated modeling tool for use by the ALS community. Using such a tool, systems level modeling, simulation, and analysis of ALSS can be performed using up-to-date research results, and made widely accessible.

Acknowledgements

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