Designing the Greenhouse to Fit the Needs of the Plant

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Introduction

The specific greenhouse structure, the crop production system, the environmental control and the labor/management procedures, directly affect the greenhouse manager to successfully produce high quality crops within the greenhouse. The greenhouse design requires the selection of many individual component systems, within the three primary areas related to automation, culture and environment. The complexity of the dynamic greenhouse system requires that problem solving and planning should not occur with the daily management decisions, but during the design stage of the greenhouse, prior to implementation. A logical procedure of design steps is required to avoid the trial and error methodologies typically utilized, and whose success or failure depends totally on the past experiences of the designer, with too little input from the grower. Although a detailed design procedure does not currently exist, the basis for its development will be considered in this paper.

Plant and Grower Needs

The greenhouse designer must first determine the expectations and needs of the grower. The grower must then describe what crop(s) will be grown, how they will be managed, and within what basic type of growing system they will be grown. These are based on the grower/manager experiences. With this basic information, a workable design can be completed, and then modified by the financial realities of the required investment. Information obtained from the grower, should include initial planning ideas, "forward thinking" for the future, and even some philosophy about the greenhouse design.

Grower and designer dialog might begin as follows:

1) What are your expectations for this endeavor? Where do you want the business to be in the future? How much expansion can occur? What is a comfortable size, or production capacity for you? What are the land, or other resource limitations?

2) What greenhouse systems are of most interest to you? Which are an absolute necessity in any design for you? For example, the type of crop production system which is based on your plant growing experiences should not be compromised. However, with limited capital available, try to obtain the most cost-effective return that will successfully produce the crop, even if the design is initially not the most optimal. Do not block future design improvements and expansion relating to new crops, mechanization, automation, environmental restrictions.

3) With the amount of money available for the initial capital investment, determine the amount of capital investment ($\$/ft^2$) of greenhouse area is possible based on your initial size requirements. Include the most necessary systems and components, especially those which cannot easily be added later. Design all the systems with these future improvements in mind.

4) Selection (or elimination) of specific systems should be based on whether it is an immediate necessity, or a desirable "tool". With insufficient capital, it is important to select the additions to the overall system with the most return for the investment. For example, an energy blanket is typically a very cost-effective investment. The cost is approximately $\$2.50/ft^2$ ($\$27/m^2$), and energy savings can approach 35%. With large yearly heating energy costs, this investment is good. However, it could be installed at a later date, if the greenhouse structure is designed properly. Another example is the structural foundation which should be considered initially, or it will be completed later at much greater expense. This might include a poured concrete footing, with an 8 inch (20 cm) high concrete knee-wall that extends below soil grade, and has a 3 ft (90 cm) "splash pad" around the entire exterior perimeter of the foundation. This reduces dirt splash onto sidewall glazing, keeps weeds away from sidewall, and is a good barrier to rodents. Ventilation is an absolute requirement but the complexity of a multi-staged fan and inlet window system could be simplified to a single stage system to reduce initial costs. A future upgrade to a more optimum air temperature control could expand from a single stage fan and an inlet window. It is important to compromise at this point to obtain a workable, not the most optimal, greenhouse system. However, the initial design should not prevent future upgrading.

Application of Design Requirements

Assume a reasonable greenhouse layout, given the land area which is available. Begin with a small, but complete unit, with a plan for successive additions to this small unit, or with modular blocks of larger greenhouses. Consider the location and size of a subsequent headhouse work area, and office space. Build in units no larger than 1 acre (0.45 ha) blocks.

The location must be a suitable site for a greenhouse. The land should be reasonably well drained and level, with access to transport of materials and product. Utilities such as fuel, electrical power, telephone, and computer should be readily available. Sufficient quantity of good quality water (care for the pH, hardness, salinity, dissolved minerals, etc.) is a necessity.

The structural integrity of the greenhouse must be sufficient for the weather conditions (winds, snow) of the location. The greenhouse structure must not only be of sufficient overall size, but also of unit proportion, primarily to fit the modular size (row spacing or bench width) of the crop production system. High productivity is, in part, based on the optimum use of greenhouse space. For example, if multi-truss greenhouse tomatoes are to be produced within a double-row and aisle growing system, one possible design consists of a pair of tomato rows within an 18 in (45 cm) wide bed, and adjacent to a 30 in (76 cm) aisle. The replicate unit space requirement of the growing system would be 48 in (122 cm). Therefore the unit width of the greenhouse bay should be a multiple of 4 ft (1.2 m). Commonly available sizes would be 20 or 24 ft (6.1 or 7.3 m) from gutter to gutter.

An important consideration for long-term expansion is whether a ground to ground (Quonset style), or gutter-connected structure should be selected. The Quonset can initially be less expensive. However its maximum width is limited to approximately 28 to 30 ft (8.5 - 9.2 m), and it cannot easily be expanded. The next Quonset unit would have to be built adjacent to the first, with separate entrance, environmental control system, and other required systems. The land space in between each unit is not easily usable, and requires maintenance. The gutter-connected design allows for easy future expansion by moving the sidewall and adding more bays in between. The entire module is under one roof, which provides for common access and the capability of sharing mechanization and environmental control systems. There can also be a significant economy of scale, not only in long-term capital investment, but also in yearly operational costs. For example, within NJ climate conditions, heating costs savings alone justify the use of one large gutter-connected greenhouse instead of five separated 20 ft (6.1m) wide units. Labor management and crop culture, although hard to quantify, seem readily improved within one large facility, as compared to management of numerous smaller units. Multiple, separate structures can potentially offer isolation for disease and insect control, which seems less possible within gutter-connected facilities. However, pest control practices are more difficult and time consuming in separated, smaller structures. Practical isolation is difficult because of the labor tasks requiring regular, and intimate plant contact. The realities of the situation are analogous to successfully creating a non-smoking section on an airplane!

Greenhouse Orientation

Greenhouse orientation, as determined by the direction of the ridge or gutters, relative to the movement of the sun, is of major concern and continuous debate. There may be no optimal compass orientation, but there are costs and benefits to be considered between each. The concern is for the maximum quantity, duration and uniform availability of solar radiation for plant growth. At geographic locations greater than 30^o north or south from the equator, the natural, seasonal reduction of solar radiation is THE most limiting factor in plant growth and development. It also can be the most difficult and expensive to overcome. For example, the yield and quality of greenhouse vegetables such as tomatoes are directly affected by light availability. For latitudes near 50^o north, experience has shown from 1 to 1.5% loss in tomato yield for each 1% reduction of light received at the plant canopy.

In general, the free-standing, Quonset greenhouse will provide more solar radiation than a gutter-connected greenhouse, with similar orientation. For gutter-connected greenhouses, in a N-S ridge orientation, the most total yearly amount of light will be received. Much of this light, however, is received in the summer season. Considering only the winter season, that is, the lowest light intensity and shortest daylength period of the year, an E-W ridge orientation will gain more total light than a N-S orientation. It is important to determine what crops will be grown, their light requirements, and when the crops will be grown, prior to selecting and orienting the greenhouse structure.

For uniformity of light distribution at the plant canopy, the N-S oriented greenhouse is always better than the E-W. The shadow patterns caused by the N-S gutters constantly move across the crops (from west to east), as the sun travels from sunrise in the east to sunset in the west. This is especially important during the light-limiting season, so that all plants receive similar daily amounts of light. In an E-W greenhouse, the shadow of the gutter moves toward the south as the sun rises in the morning, and toward the north afternoon, as the sun begins setting. The distance of this shadow movement becomes quite short during the low sun angles of the winter season. Thus several rows of plants within each bay will be in continual shadow, and subsequently will have reduced growth rates. This assumes clear sky (direct beam radiation) conditions. With cloudy, diffuse sky conditions, the shadow effect is diminished but not totally eliminated. For a tall crop of multi-truss tomatoes, the most optimum orientation for year round production is with the greenhouse oriented N-S, and with the rows of plants oriented parallel to the gutters, that is, N-S as well. This again is based on the above described importance of light distribution uniformity, but also on the fact that the plants in N-S rows would receive morning light on their east side and afternoon light on their west side. The entire portion of the plant would be in direct light at some time during the day, whereas with an E-W orientation, the entire north side of the plant and much of the lower portions of the south side would continually be in shadow during much of the winter season. For a short crop such as lettuce, an E-W orientation of the growing system would be acceptable because plant to plant shading is minimal. However, E-W rows within a N-S greenhouse causes some difficulties in the layout and operation of the growing system.

Environmental Control

Environmental control for heating and cooling uniformity is a very important design consideration. The process of sizing the heating and cooling systems can provide sufficient cooling or heating. However, it cannot be assumed that a uniform environment will occur for each plant within the greenhouse. Non-uniform environments cause differential plant growth rates, potential disease problems, unpredictable results with nutrition or hormonal application, and generally a more difficult plant production system to manage.

For the most effective and uniform cooling with fan ventilation, the rows of tall plants should be arranged in the direction parallel with the ridge or gutters of the greenhouse structure. This is less critical for natural ventilation systems, and for production of short plants such as lettuce. This assumes that the ventilation system (fans and air inlets) would be located on the fixed endwalls, not on the sidewalls which extend parallel to the gutters. Future expansion of the greenhouse could readily occur without the need to move the existing fans and air inlets, by moving the sidewalls outward and adding more bays in between. This design allows for the air to move through each aisle between the rows, as it travels from inlet to fan. Should the plant rows run perpendicular to the ridge or gutters, uniform air flow would be significantly reduced within a tall crop. The rows of plants adjacent to the inlets would block the airflow as it entered the greenhouse, and cause the air to channel around the plant rows and into the open pathway(s). The pathways within this layout would have to run parallel to the gutters at one or both ends of the plant rows. They provide the access to each row of plants for labor tasks. However, they would also provide the easiest, and most direct channel for the incoming ventilation air to reach the exhaust fans, without passing within the plant canopy. Plant cooling uniformity would be poor.

Should airflow be made restricted and non-uniform, for whatever reason, then the ventilation system cannot effectively cool the plant, nor provide for sufficient air exchange for disease control and carbon dioxide availability. The operational efficiency of cooling and heating systems is therefore reduced, and operation costs will increase. The evaporative cooling system, whether Pad & Fan, or high-pressure fog, are highly dependent upon effective and uniform ventilation. Air heating systems which are highly dependent upon unrestricted air movement to each plant, will also be less efficient. Fuel and electrical cost would increase. The rate of plant growth would vary in proportion to the temperature variations at different locations within the growing area. Less than optimal air temperature and humidity may cause an increase in plant pathological disorders, and make efforts to reduce pest and disease pressure more difficult by restricting the dispersion of pesticides.

A hot water heating system is less affected than a hot air system, by plant row direction within the greenhouse for distributing the heat to the plants. The heating pipe network is uniformly spaced throughout the entire greenhouse area, and typically distributes the heat more uniformly. In some cases, it is desired to place the hot water pipe system near the base of the plant, or within the aisle. The air at the floor is heated and rises through the plant canopy, providing a highly desirable plant microclimate. For this situation, the plumbing of the pipe network could be more difficult and potentially expensive when the plant rows are not parallel to the direction of the greenhouse roof

ridge or gutters.
The design should also consider energy consumption for heating or cooling. Should the long term expectations be for a production facility which is larger in growing area than four, freestanding structures can provide, then it is generally more energy efficient to construct one larger gutter connected module. The heating energy savings is gained by the reduced proportion of the sidewalls relative to the floor area within a gutter-connected greenhouse.
For improved climate uniformity, a taller greenhouse is better. In gutter-connected greenhouses, a minimum of 10 –12 ft (3 – 3.7m) from floor surface to gutter height, which also provides an additional 3 or 4 ft (0.9 to 1.2 m) from the gutter up to the ridge, is desirable. Many recent constructions have gutter heights of 14 ft (4.3 m) or more. These designs provide a large internal air volume, which helps to modulate the natural fluctuations of the environmental conditions. The larger volume is particularly helpful in maintaining desired air temperatures during the warm seasons. The solar heated air accumulates in the high spaces, allowing the cooler air to remain at the plant location. The added height for a tall greenhouse does not significantly increase the energy required for heating, particularly on a gutter-connected greenhouse. For example, when the gutter height is increased 20%, from 10 to 12 ft (3 to 3.7 m) within a 36 by 100 ft (9.1 by 30 m), three bay, gutter connected greenhouse, the surface area increases by only 8%. Note that the surface area, not the volume of the greenhouse, determines the design size of the heating system. For larger greenhouses with greater floor areas, the wall surface area is proportionally even less significant.
In addition to better climate control within a tall greenhouse, vertical space may be required for other greenhouse systems such as: an energy blanket or shade cloth, supplemental lights, benches (reducing the available height to the overhead systems), tall crops such as tomatoes, irrigation boom or overhead misting systems (not for tomato production), or future hanging basket plants. The ridge height and volume of interior space within Quonset-style greenhouse, is typically less than a gutter-connected greenhouse with similar floor areas.
The most common energy conservation technique related directly to the design of the structure is the internal energy blanket. This system could also be used as a shading device with proper selection of blanket material. In all greenhouse structure designs, a space for the energy blanket should be provided. Within a gutter-connected greenhouse, the blanket can be located at the height of the gutter. When not in use it can be tightly packed beneath the gutter to minimize additional shading and loss of light to the plants during the day. The energy blanket can be installed within Quonset-style greenhouses but with more difficulty and more shading of the crop. In all cases where the winter season requires significant amounts of supplemental heating, the energy blanket provides a cost effective means of energy conservation. For example, the design size of the heater required for a greenhouse with an energy blanket can be reduced by 30 to 35%, as compared to the same structure without an energy blanket. An energy blanket system can cost \$2.50/ft^2 (\$27/m^2).

Management and Labor
Management and labor for crop production is generally the greatest expense for a greenhouse operation. Any means within greenhouse design to increase labor productivity or improve labor management is beneficial. Generally a larger facility under one roof, such as with gutter-connected greenhouse designs, can improve the labor management situation. Employees are confined to a single location, and not among numerous smaller structures. The preparation and work areas for specific tasks can be centralized for more efficient labor productivity. Supplies and raw materials can be readily available from central storage.

The somewhat structured conditions of a greenhouse has an advantage over other forms of production agriculture. The work conditions can be modified and improved as a result of the mechanization, automation, or environmental control systems. The labor demand is quite regular, which helps to maintain a skilled, dependable workforce. The regularity and repetitiveness of the work tasks allows for analysis and improvements of work conditions and procedures, which ultimately lead to increased productivity and safety for the worker. These attributes should be used to the advantage of the greenhouse designer and the greenhouse manager. Even relatively simple improvements can greatly increase worker productivity. For example, a wheeled cart which rides on the heating pipes located within the aisles between the tomato rows, improves harvest rates and potentially reduces fruit damage.

Materials and Product Flow, Internal Transport and Space Utilization

The layout of a greenhouse production area affects the productivity of both the greenhouse and the workers. One indication of greenhouse productivity is measured by the space utilization. Labor productivity is influenced by the sequence of tasks to be performed within the greenhouse, and the management strategy. The flow of materials and salable product can be directly influenced by the greenhouse structure and the layout of the internal systems. The greenhouse consists of specific locations for plant production, internal transport, and preparation tasks for input or output. These locations need to be considered in advance of the structural layout, to best meet the production demands.

The plant production space within the greenhouse bays, account for the largest of these locations. The type of growing system, its physical layout, and its environment and plant culture systems (water, nutrients, heat) directly affects labor efficiency and flow of materials. Within the plant production space, the greenhouse bays consist of crop rows which are typically organized in a repetitive fashion. The bays have aisles for worker access to the plants. It is desirable to minimize both the number and the size of the aisles, in order to optimize the greenhouse floor space for plant production. The limitations on these minimum sizes are based on the light availability to the plant canopy, and the need for sufficient access to the plants to complete the tasks associated with plant care, maintenance, and most importantly, harvest.

The crop rows within the bay must be inter-connected to each other for easy access by the workers, as well as, to the input/output location of the greenhouse. This connection is completed by the main pathways. The number and size of pathways need to be minimized, however, they must be of sufficient capacity to prevent labor or transport bottlenecks. They should be sized for the required machinery that must be transported. There must be at least one main pathway which extends from the shed, and connects to other pathways, or directly to each row of each bay. It is important to minimize the transport distance whenever possible.

The shed is the main input and output location of the greenhouse structure, and should be located on the north side of the greenhouse. It may range in size from an entire building attached to the greenhouse, to a small entrance vestibule located immediately inside the greenhouse door of the production area. The size of the shed depends on the type of work and amount of work to be performed there, as well as the need for storage of materials there. This may be the preparation area for the raw materials prior to transplant, and it may become the final preparation area for the harvested product prior to shipping. Material flow and organization of the workspace and work patterns is critical within the shed, as it is the primary bottleneck of the entire greenhouse operation.

Automation, Mechanization and Labor Aids

The greenhouse is like a factory. Raw materials (soil mixes, containers, seeds or seedlings, fertilizer, water) enter the greenhouse. They may be stored in the raw form, or utilized in the process immediately. Finally a product is shipped for sale. During the time the plants reside in the greenhouse, the culture processes including the grower's expertise, care and nurturing ability encourage the plants to grow and mature. For many crops, the cultural work is directly related to the physical requirements associated with transport and materials handling. For others, plant maintenance operations (eg. pruning pinching, pest control, etc) performed during the growth period, do not require plant transport. However, the worker must travel to the plants. It is logical then that transport of the crop be efficient and easy for input and output operations, and that access to the plant be relatively unrestrictive for the maintenance operations. This is especially important for crops requiring regular "hands-on" maintenance tasks. The importance of mechanization and automation is directly proportional to the of handling and maintenance operations required for the crop.   Two crucial considerations are whether the crop requires regular (daily) transport during its growth period, and whether the operations can remain within the greenhouse growing area, or whether they must include travel to a work area outside the growing area. A general rule of internal transport is, if transport is required, than move the largest amount of materials or crop over the shortest possible distance during each transport cycle.

If efficient transportation is a part of the greenhouse design, then there are several options for locating the work area (ie the area where hands-on maintenance operations will be performed on the crop). It could be near the production area, or completely removed from the production area, for example within an adjacent shed. There would also be the option for a mobile work area, which could move throughout the main pathways of the greenhouse. This essentially requires mounting the necessary equipment or machinery onto a movable platform.

Machinery and hand equipment which can improve the capability of the workers to perform their tasks, or improve the working conditions while completing their tasks should be considered in the design. Conversely, certain greenhouse layouts and crop culture techniques should be avoided to prevent difficult labor conditions. Any design which requires regular, extremely strenuous or exhaustive laborous work should be considered for redesign. Although machinery and equipment can reduce the difficulty of a labor task, it is better to avoid the added expense, if an alternative design can eliminate the need to mechanize.

Automation within a production system can have many attributes. It also has an investment cost which must outweigh the costs of a manual operation. Automated machinery or manual labor aids increase the uniformity and consistency of the product, and the work force. Mechanization of an operation can provide mechanical power, speed, repetition, safety and potential for consistency and quality control. Automation includes these attributes but with greater flexibility and potentially some decision-making. The financial value of increased quality offered by automation or mechanization may be difficult to determine, but an increase of quantity or production capacity can be readily calculated.

Plant Culture System

The plant culture system is usually the easiest of all systems for the grower to understand and design, primarily because plant production is the basis of his profession. The final system selection is usually based on the grower's past crop production experiences. It is not recommended for any new and/or large facility to change the crop production system dramatically from the previous experience of the grower of the facility. For example, a grower experienced in multi-truss tomato production within soilless media, should not establish a facility of hydroponically grown, singletruss tomatoes. A small test trial would be the best approach. The plant culture system consists of the root zone and aerial environments. These include the root growing media, the water/nutrient distribution system, and the crop physical support system. Both the root and the aerial zones of the plant are directly affected by the characteristics and limitations of the culture system. The culture system is primarily described by the type of hydroponic, soilless culture or water delivery mechanism employed. Since watering is fundamental and crucial to the quality of the plant, water and nutrient delivery become vitally important. There are many specific types of water delivery systems (NFT, Ebb and Flood, drip irrigation, etc.) and numerous variations within each type. The general requirements which are common to most of the successful crop production systems can be described by their type of: (1) plant support, (2) root zone containment, (3) nutrient/water distribution, (4) root zone aeration, and (5) environmental conditions.   Once the type of plant growing system is selected, the design efforts must focus on the specifics of a water delivery system. The root zone media and the crop water requirements determine the parameters of design of the water distribution system.

Many of the biological processes required for the culture systems are inherently served by the specific procedure in which water and nutrients are delivered to the plants. Processes such as transpiration, respiration, nutrient uptake, gas exchange, and organic waste product removal are enhanced or inhibited as a direct result of root zone watering. The characteristics of the water delivery system influence the controlling parameters of each of these processes, and therefore modulate their relative activity, and indirectly affect the growth and development of the plant as well. Several important characteristics of the watering system include: (1) the nutrient solution transport/flow pattern within the root zone, (2) the buffering capacity of the root zone, (3) whether the nutrient solution is recirculated or "drained to waste", and (4) the frequency and duration of application.

Frequency and duration of nutrient solution flow is dependent upon the characteristics of the culture system and the physiological age and water demand of the plant species under production. Flow patterns and buffering capacity at the root zone, and whether an open (non-recirculation) or closed (recirculation) watering procedure is employed, all directly influence management procedures. All of the above are further modified by the environmental conditions supplied to the plant.

Plant culture includes the fundamental parameters which influence the growth and development of the plant. The basic needs particular to the plant to be grown must first be determined. Then how the interaction of cultural procedures with the controlled environment, and the materials handling system, will affect the final plant product must be considered.

Re-Consideration of the Design

Given a crop and its necessary culture requirements, the crop production system with its particular water/nutrient delivery system can be selected. Once labor needs and environmental controls are determined, then a greenhouse structure can be constructed for all of the internal systems. This is the basic procedure envisioned, and described in the paper. However, if the initial design seems too unproven, or has too many unknown components, than a re-design may be necessary, and usually is necessary. The designer should review the entire design process, but should focus on the sections of this paper beginning with Management and Labor, and then proceed to the end. Design is an iterative process, and good design is a long, iterative process. People are finicky about their real needs, and will change priorities. Greenhouse growers are no exception.

Integration of the crop production and the environmental control systems within the system of automation is an important aspect of greenhouse design. Culture systems capable of supporting plant growth must be compatible with the materials handling and automation systems, as well as the labor expertise and demands required to operate the system.

Design and operation of a greenhouse for plant production are daunting tasks even for the most experienced persons. They are a highly complex system of individual biological and mechanical subsystems. These subsystems are deeply interrelated and must function together to provide successful crop production. With fundamental understanding and a desire to develop integrated crop production systems, the design of future greenhouses may become less guesswork, or determinations by "experience", and more methodical and reliant on information databases.

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References

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Appendix

Some complementary thoughts:

Heating system

Initially it would be less expensive to use unit heaters (water to air heat exchangers) within each bay. The plumbing that carries water from the boilers to the unit heaters would be sized to later be able to connect into overhead distribute hot water heating pipes (a more expensive but better heating system design). Have separate boiler systems for each of the 1 acre sections, then later when 3 or more sections are built, combine boilers into one centralized boiler room.

Operate the boilers during the day to warm the concrete floor heating system and utilize the carbon dioxide from the boiler exhaust. Have the floor system as the primary heating source whenever possible, and utilize the overheads to provide the difference in heat energy required.

Layout and Daily Operational Management

The physical design and layout of the greenhouse will directly affect the daily management of the operation. After construction of the centralized headhouse building it will become clear why the greenhouse sections were arranged relative to the headhouse. One grower found that one operation that before took three days, afterwards required only one day.

What is your management structure? This will also directly influence the operation with the given greenhouse layout.

Have one foreman (grower/manager) for each section, thus it will be very clear who has responsibility for production within what area. This will provide an easy means to monitor each of their performances. Then it is possible to reward good performance, and provide incentive for improvements. This helps to keep quality and quality laborers for the managers.

Consider maintenance. Keep a regular maintenance program. Do not wait until a major problem occurs when it is unexpected. A well-maintained operation gives a good example to the workers as well. It is a self-feeding program with many benefits.

Select the height of the greenhouse.
It is difficult to make the greenhouse too tall. Why are such heights (10, 12 or 16 feet to the gutter) so important? a larger volume is easier to (environmentally) control especially within a warm climate area; supplemental lights (if desired) must be installed under the energy blanket; room will possibly be needed for hanging baskets; an optional irrigation boom needs clear overhead space for transport; transportable or rolling benches may substitute for the floor growing system in the future, which will reduce the effective plant canopy to gutter distance.

An example system design cost
Assuming 4 sections of one acre area each, with 3 sections of double poly roof and one section of A-frame glass, and sidewalls of Exolite polycarbonate, with a headhouse, the estimated cost is 14 - 15 $/f2 of growing area. For only the 4 acres of greenhouse the cost is 7 $/ft2.
Materials handling, crop transport and completion of labor tasks are necessary activities within all controlled environment plant production (CEPPS). Management of materials and resources for completion of the multitude of plant culture operations (eg potting, transplanting, harvesting, watering, etc) is required. Nearly all the operations require transport of materials or movement of labor. The proper design of automated systems integrating transportation and robotic capabilities can greatly enhance the efforts of the manager, and the overall production system performance.