HARNESSING COMPLEXITY IN DESIGN

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Large scale design problems involve complex systems. The complexity arises from the nature of the large interconnected systems and is escalated by the background, personal characteristics, and perspectives of the individuals working on the design team. It is important for designers to understand complexity and how complexity affects the understanding and prediction of system behavior. It is even more important to manage the complexity such that it does not overwhelm the design effort and prevent the development of effective solutions. This paper presents an overview of complexity, discusses how complexity can increase almost with out bound, and suggests ways to control the impact of complexity on design processes.

1. Introduction

The world’s population continues to increase rapidly. Technology is developing at a geometric pace. Modern communication systems provide each of us overwhelming mountains of information, much of which is unorganized, not relevant, redundant, or inaccurate; and thus, may well provide more confusion than clarity. We are faced with the necessity to wrestle with and solve many large–scale problems if we are to maintain sources of clean water, clean air, food, energy, adequate medical services, political stability, and a civilized social structure. Improving the condition of our world will prove even more difficult.
The large-scale problems with which mankind must deal include not only the design of engineering systems with numerous components and subsystems with interact in multiple and intricate ways; they also involve the design or redesign of social, political, managerial, commercial, religious, biological, medical, etc. systems. Further, these large-scale systems are likely to be dynamic and adaptive in nature. Herb Simon stated

*Today, complexity is a word that is much in fashion. We have learned very well that many of the systems that we are trying to deal with in our contemporary science and engineering are very complex indeed. They are so complex that it is not obvious that the powerful tricks and procedures that served us for four centuries or more in the development of modern science and engineering will enable us to understand and deal with them. We are learning that we need a science of complex systems, and we are beginning to construct it* [Simon, 2000].

In *The Sciences of the Artificial* Simon further states

*The proper study of mankind is the science of design, not only as the professional component of a technical education but as a core discipline for every liberally educated person* [Simon, 1999].

Thus, we may conclude from Simon’s words and from our own deliberate consideration of on-going efforts to wrestle with complex problems, that complexity is a major obstacle and design and process are the keys to solutions of the large-scale problems. Our success in solving complex problems through design will depend largely on our ability to manage the complexity associated with these problems.

The rapid expansion of technology has and will continue to provide tools which can assist with the management of complexity in design projects. However, we must understand how complexity affects the design of large-scale systems and how complexity escalates from both situational and cognitive aspects. Warfield [1994] defines two kinds of complexity: *situational complexity* or those aspects of the system or problem that are not known, observed, understood, or available to the designer and *cognitive complexity* as variation in interpretation of system aspects due to each individual’s biases based on his or her past experiences.

In this paper we consider what is meant by complexity and the difficulties that complexity brings to the design of large systems. We explore the effect of complexity escalation and we propose a strategy to manage complexity associated with the design of large systems.

2. What is Complexity?

It will be useful to develop a working definition of complexity and complex problems. Are systems complex in their own right or are do they seem complex only because we do not understand all of the intricacies and interactions involved? Webster’s *Ninth New Collegiate Dictionary* provides the following characteristics for complexity

*composed of two or more parts; the unavoidable result of a necessary combining; offers great difficulty in understanding, solving, or explaining; the interlacing of parts so as to make it nearly impossible to follow or grasp them separately; extreme complication and often disorder; complication and entanglement that make solution or understanding improbable* [Webster’s, 1988].

From Webster’s input we can infer that complexity or complex systems involve multiple and likely numerous parts, interaction, interlacing and entanglement of those parts, and are difficult to understand or explain. Often, very complex phenomena or systems may appear from a cursory examination to be simple.
Axelrod and Cohen [Axelrod and Cohen, 1999] state that complexity stems from fundamental causes and cannot always be eliminated. They further comment While complex systems may be hard to predict, they may also have a good deal of structure and permit improvement by thoughtful intervention. Thus, identifying the structure of a problem may be one means to deal with its complexity.

Axelrod and Cohen also embrace the idea presented by Murray Gell–Mann [1995] which proposes that complex systems are hard to predict not because they are random, but because their regularities cannot be briefly described. Thus, complexity is differentiated from randomness. Axelrod and Cohen define Complex Adaptive Systems that are composed of populations of agents and artifacts. The agents, who have location, capabilities, and memory, can formulate strategies, interact with other agents, and manipulate the artifacts. The artifacts are objects used by the agents and they also have properties such as location and capabilities. Agents, which include individuals, groups, political entities, computer software, etc., can intervene and cause variation and adaptation and they can remember the results of previous interventions, and thus, make selective interventions.

Wolfram [2002] proposes that complexity in a system as indicated by the randomness produced, can come from 3 sources. The first source of randomness is the explicit and continual intervention in the system by its environment. This scenario could be related to Axelrod and Cohen’s concept of agents with memory providing selective intervention. The second source of complexity is derived from random or complex initial conditions to which the system is subjected. This source is of less interest in terms of managing complexity in design because the effects of initial conditions are generally short lived due to other influences internal to the system. These first two sources depend on external influences to provide complexity in the system, whereas, Wolfram’s third source of complexity is intrinsic to the system itself. That is the system can generate complexity without input from its environment. Large–scale systems that we wish to design may exhibit characteristics of Wolfram’s first and third sources of complexity. Medical systems, social welfare systems, political systems, etc. that directly involve people as part of the functioning of the system certainly could be envisioned as having agents intervening and they certainly will generate complexity due to the interactions of the people and subsystems. One might however, define the agents and their intervention as part of the system rather than the system’s environment in which case Wolfram’s third rule would best describe the generation of complexity. Wolfram makes the case that the third rule applies to most natural systems. We should point out that Wolfram uses the randomness generated as an indication of complexity. As indicated by Axelrod and Cohen, complexity can be present and increase without randomness. We feel that Wolfram’s comments on the sources or complexity in terms of randomness can also be applied to the generation of complexity in large–scale systems as indicated above.

Simon [1999] notes that during the previous century there were several bursts of interest in complexity and complex systems. After World War I there was interest in holism and creative evolution. Following World War II expressions such as information, feedback, cybernetics, and general systems became popular. During the latter part of the century and currently complexity is associated with chaos, adaptive systems, genetic algorithms, and cellular automata. These later ideas shed light on the context in which we will consider complexity and complex systems. Large–scale systems certainly exhibit the characteristics of chaos, where chaotic behavior does not imply randomness, and adaptation caused by interference from various agents within the system. Simon further discusses the term Catastrophe in term of complexity. In this context he is referring to systems which change from stable behavior patterns to extremely unstable behavior due to a relatively small perturbation or intervention. A simple example relates to personnel management, perhaps the difficulties of an inexperienced manager during an early opportunity to exercise his leadership skills. Because the young manager does not fully understand how to motivate others, he issues a change in policy intended to increase productivity which instead creates confusion and possibly dissatisfaction among his work force and actually decreases productivity. Implicit in this example are the
complexity of social and professional interpersonal relations and interactions and the adaptation of people to new situations.

A couple of additional quotes from Simon note that while the study of complex systems is not a new phenomena, the interest in complexity as a subject is perhaps coming of age and they help to characterize Simon’s concept of complex systems.

*Complexity is more and more acknowledged to be a key characteristic of the world we live in and of the systems that cohabit our world. It is not new for science to attempt to understand complex systems: astronomers have been at it for millennia, and biologists, economists, psychologists, and others joined them some generations ago. What is new about the present activity is not the study of particular complex systems but the study of the phenomenon of complexity in its own right* [Simon, 1999].

The four aspects of complex systems according to Simon are:
1. Complex systems are frequently hierarchical.
2. The structure of complex systems emerges through evolutionary processes and that hieratic systems will evolve much more rapidly than non–hierarchic systems.
3. Hierarchically organized complex systems may be decomposed into sub–systems for analysis of their behavior.
4. Because of their hierarchical nature, complex systems can frequently be described, or represented, in terms of a relatively simple set of symbols.

We can conclude from these four statements that complex systems, at least ones that are likely to be of interest to us, are not random, but rather, have structure. This assertion agrees with Axelrod and Cohen’s comments presented earlier. Further this structure is based on the interactions between the various parts (components and sub–systems) of the system. Simon also indicates that complex systems, because of their hierarchical nature, evolve and change rapidly with time. Axelrod and Cohen describe the adaptation of systems due to the intervention of agents (agents are individuals, organizations, political entities, computer software routines, etc.). Simon’s third aspect of complex systems indicates a likelihood that they can be decomposed for study and analysis. This characteristic, which provides hope for dealing with complex systems, may not be easily realized. The interconnections and interactions of the parts of a complex system will not typically be obvious without significant study. Finally, Simon observes that complex systems can frequently be represented by seemingly simple arrangements of symbols which follow from the hierarchical structure of the system.

Warfield expresses his view of complex systems a bit differently.

*For better or worse, our society has accepted the idea of large and complex systems. If we are going to have them, it behooves us to learn how to manage them* [Warfield, 1994].

*One of the primary motivations comes from recognizing that society today involves large sociotechnical systems whose performance is far from ideal. It is clear that many of these large systems have taken their present forms primarily through evolutionary change that did not involve any systematic overview design, but may have involved some systematic design of parts. Other systems are said to have been designed, but still fail in ways that produce disasters.* [Warfield, 1994].
Warfield defines three classes of systems: Class A systems consist of parts founded in the physical sciences, Class B systems members are intellectual technology or products of artificial intelligence, and Class C systems include both Class A and Class B type members. Integration of the Class A and Class B type members into synergistic units is necessary for Class C systems to perform satisfactorily. Primary standards common to science and engineering provide eternal referents which can be used to gauge the performance of Class A systems. Because such fundamental yardsticks are not readily available to measure the performance of Class B and Class C systems, designers must develop appropriate means to properly conceptualize such systems. Warfield defines a sociotechnical system as a mix of technology and people which depends on a synergistic interaction of the technology and the people for satisfactory performance. Although Warfield’s comments are cast in a different context, they do not essentially disagree with the previous discussion.

In summary, we would define a complex system or complex problem as one which contains many components and subsystems organized in a hierarchical fashion and which have multiple, non-linear interconnections that are difficult to understand, recognize and predict. Further a complex system involves agents, people, organizations, political entities, computer software, etc. capable of creating, destroying, or changing system parts and sub-systems and adapting the interactions among parts and sub-systems. The solution of such problems and the design of such systems is truly a transdisciplinary process and requires every means to reduce or manage the complexity associated with the system.

3. Two Aspects of Complexity

The definition of a word and its meaning are not necessarily the same. The definition of a word is a formal statement from a source of some authority such as a dictionary; whereas, the meaning depends on the personal interpretation by each individual. Personal interpretations depend to a great extent on the background and experiences of the individual, not on a formal recorded definition. Much time and expense can be spent in attempting to align a definition with meaning, especially when two or more persons are involved. Anyone who has work on a standards committee can attest to the difficulty of getting a consensus on the meaning of specific items the standard is intended to define. Warfield asserts that there are two aspects of complexity associated with any problem. He draws upon the old question of whether sound is generated when a tree falls in the forest and no person is present to hear the sound. Clearly the answer depends on the definition of sound. The tree does fall and produce a disturbance, which we would call sound waves, in the air, or media through which the sound waves are transmitted. Thus, if we define sound as the transmission of sound waves through a media, then sound is produced. However, if we instead define sound as the image or impression in the human mind when the sound waves are intercepted by the ear and interpreted for the mind, then sound did not ensue if no one was there to hear the sound.

The first source of complexity comes from the system itself as discussed earlier. In other words the system itself emits characteristics and information which are available for interception by the human observer. How well this emitted information is collected provides insight and understanding, or lack thereof, of the system by humans. Warfield denotes this source of complexity as situational complexity. On the other hand, cognitive complexity refers to the distortion or miss-interpretation of the incoming information by the receiving person. Like the difference between the definition and meaning of a word, there are always differences between the reality of a system and the perception of the system by individuals. The complexity of a system is the sum of the situational and cognitive complexities. In other words, we human beings cannot collect and analyze enough information about complex systems to fully comprehend and understand the system, and to make matters worse, we do not interpret the information we receive correctly. Complexity might also be defined as the limitation of the human mind and its reasoning capabilities.
4. Escalation of Complexity

As if complexity was not enough, the level of complexity associated with a system can and will escalate with time. Interaction among sub–systems increase the complexity of the system. Warfield [1994] describes two aspects of complexity escalation. Systems can change and adapt, therefore the number and intricacy of sub–system interactions can increase with time. When a design team surrounds the system as is typical in conventional engineering component and simple system design problems, they can see the entire system and understand all of its ramifications and requirements. The team can also observe and understand changes in the system as they occur. However, when a large–system in effect surrounds the design team, they cannot be aware of large portions of the system and cannot fully appreciate the interactions or even all of the components and sub–systems. The team’s perception is limited. The system will change with time and more sub–systems and interactions will become visible to the team. This increase in information provides an escalation of complexity. In terms of design these changes may be changes in requirements as modified by a customer, interactions between system parts not fully recognized or understood earlier, additional impediments to meeting original or changing requirements, limitations in technology available, limitations in resources needed, etc.

The complexity escalation associated with realizing additional components and interactions within the system is the first type of escalation. Additional escalation arises when more than one individual is involved in the design process. Teams are typically employed to attack complex problems. Each member of the team will bring his or her own particular background, and thus, own perception of the components and interactions — both the originally discerned and the additional ones discovered as the process continues. The team must grapple with the various perceptions and understandings of the problem and try to resolve them into a common and accurate view. The team dynamics associated with the different interpretations and understandings, which change with time, of each facet of the problem is a critical issue. This is the second type of complexity escalation.

A related escalation of the problem is associated with the linkages among values, policies, identities, and self–interests of organizations represented by the team members. The team must produce an effective solution to the original problem that is also consistent with the new constraints imposed by the organizational culture(s) involved. It can be difficult to identify and mitigate hidden agendas and organizational motives, especially when multiple organizations are represented by the team.

There can be other escalations of the complexity of a problem. The nature of the problem may change due to adaptation of the system or because the team’s understanding of the system changes. The design target may be redefined for any of many reasons. Resources available to the project may change, usually for the worse. Incompatible organizational values or objectives may provide escalation. Typically education and training concentrate on much simpler situations for examples and ignore all important complexity escalations.

5. Human Limitations

We should mention briefly complications that result from human limitations. Earlier we indicated the problems with human perception of problems due to the influence of each individual’s experience base. Everyone has personal values, self–interests, and learned biases, hence, each person will interpret the same data differently — sometimes very differently. The various interpretations by team members can lead to confusion and arguments that distract and mislead the design process.

It has been shown [Miller, 1956] that the human mind is only capable of working with seven plus or minus two concepts or ideas at a time; the so called magic number concept. As discussed earlier, complex problems by definition have many parts, thus, it is not possible for a person to consider the interactions of
Table 1  Some Measures of the Span of Immediate Recall [Miller].

<table>
<thead>
<tr>
<th>Stimulus Set</th>
<th>Variables</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Words</td>
<td># Syllables/Word</td>
<td>5 — 7</td>
</tr>
<tr>
<td>Phrases</td>
<td># Words/Phrase</td>
<td>2 — 4</td>
</tr>
<tr>
<td>Digits</td>
<td># digits</td>
<td>8</td>
</tr>
<tr>
<td>Digits</td>
<td>Age of Subject</td>
<td>2 — 8, increasing with</td>
</tr>
<tr>
<td></td>
<td></td>
<td>age*</td>
</tr>
</tbody>
</table>

* Can be increased with persistent practice

hundreds of system parts simultaneously. Table 1 indicates some of the typical measures of the span of immediate recall. It is interesting to note that most people can recall seven digit phone numbers, but are unlikely to remember six–teen digit credit card numbers.

Wolfram [2000] indicates that his series of experiments with small programs indicates that even computer programs based on very simple rules can generate very complex results. Wolfram presents results of many types of simple programs to support his conclusions. However, it seems significant that his small programs began to generate complex results when only a small number of parameters were included; usually in the range of 4 to 8 parameters. In line with Wolfram’s theory that the simple program experiments can be related to natural phenomena, perhaps there is a relationship between Miller’s seven plus or minus two concept and Wolfram’s simple program theory.

6. Processes to Manage Complexity

We have discussed the meaning of complexity, complexity escalation, and the limitations of human beings in dealing with complexity. Now we would like suggest to a process for harnessing or managing the complexity associated with a large–scale design project. We will consider the development of a fuel cell powered sport utility vehicle (SUV), a design project recently undertaken by the Advanced Vehicle Engineering Laboratory (AVEL) at Texas Tech University (TTU), as a vehicle to explore processes that can assist in harnessing the complexity of a design project. Development of the TTU fuel cell vehicle, the TTU entry in US Department of Energy and Ford Motor Company sponsored FutureTruck 2002 competition, began with a new 2002 Ford Explorer, an 80 kW fuel cell stack, and high pressure tanks in which to store hydrogen. Development of this vehicle is truly a transdisciplinary design exercise: there are mechanical, electrical, chemical, and control components and sub–systems to be developed and integrated. Vehicle emissions, energy efficiency, and consumer acceptability are also important.

As the quotes from Simon presented above indicate, complex systems are frequently hierarchical in nature, and thus, can be decomposed into subsystems. Both Simon and Wolfram indicate that complex hierarchical systems can be represented in terms of simple symbols or rules. Hence, all one need do is discover the simple representation of the system and decompose the system into its parts. If necessary the sub–systems can also be decomposed along similar lines until a manageable hierarchy of systems and sub–systems is reached. This process is not easy to accomplish.

First, any large–scale design project will require a team effort — probably a large team. Teams, especially large teams, do not just happen. A manager cannot merely identify a number of persons and form an effective team, even if the appointed teams members represent all of the knowledge areas related to the project. It takes some amount of time for team members to develop confidence and trust in each other. Confidence and trust are built on interactions and relationships. The teams members must learn to
Communicate effectively among themselves. Face to face interactions are best, but there is no reason that internet or other electronic communication and interfacing cannot provide a healthy team environment. Confidence, trust, and a good working relationship can be attained with effort, frequent communication, and time.

Large teams should be organized to compliment the hierarchical nature of the system to be designed. That does not imply a hard vertical structure, rather, a combination of vertical and horizontal structures is needed. The horizontal aspect of the structure provides for easy and frequent communication among sub–teams working of the details of various sub–systems that must interact. In hierarchical systems not all sub–systems directly interact with each other, thus, every sub–team will not need to communicate directly or frequently with every other sub–team. The vertical aspect of the team structure provides a unifying effect on the overall team by defining the relationships of the various sub–systems and related sub–groups and it provides the capability to continually reorganize the sub–teams as required during the design process.

Frequent and regular meetings of the team members are very important. Members of sub–teams should communicate at least daily about the details of the sub–systems on which they are working. Sub–groups working on interacting sub–systems should meet at least weekly to ensure that the respective sub–systems are compatible. The entire team should meet frequently to ensure that everyone involved with the project has an understanding of how the overall project is progressing and is able to keep his or her part in perspective to the whole. Meetings, especially of the larger groups, do not require that everyone literally meet face to face at one location. Internet, or televised meetings can be very effective, particularly if two way communication is available.

The fuel cell vehicle development team was comprised of undergraduate students, graduate students, technicians, and faculty advisors — about 10 graduate students, about 50 undergraduate students, 2 technicians, and 2 faculty advisors. The students were divided into several sub–groups. Each subgroup was assigned to a specific portion or sub–system of the vehicle; however, everyone was expected to be familiar with the vehicle in general and members of one sub–group frequently worked with other sub–groups to accomplish specific tasks. Regular weekly meetings of the entire team were held. During the weekly meetings, each sub–group would summarize accomplishments, problems, decisions made during the last week and anticipated accomplishments, etc. for the upcoming week. Thus, all team members were kept aware of what other sub–groups were doing and what decisions that might affect their activities were being made by other sub–groups. It should also be noted that the vehicle design team membership was about 50% of the total each semester of the year long effort, thus, at any one time the team consisted of approximately 35 students.

It is very important for all team members to understand the basic objective of the project and how their part fits into the whole. An iterative process that must begin immediately and continue throughout the entire project involves defining the project objective(s), requirements, constraints, etc. This iterative process should include the team members, customers, and stakeholders. The vertical component of the team organization should allow for the upper level sub–teams to address primarily the overall aspects of the project and the basic relationships of the major subsystems while the lower level sub–teams address the more detailed aspects of various sub–systems and the relationships among sub–systems. This process continues because the full understanding of a large–scale, complex project can only be accomplished iteratively as more of the underlying aspects become visible to the team and because the project requirements, constraints and resources will very likely change with time. To assist members of the student team with the objective of the vehicle design project and to provide as much background information as possible, a library was set–up on the internet. This library contained all information collected on fuel cells, hybrid–electric vehicles, and previous TTU vehicle projects. Team members could add any information to the library that they developed or identified as being relevant.
After the team has been organized, significantly completed their background reviews, and initiated the process to define the objective, requirements, and constraints of the project, it must then contemplate decomposing the project into sub-systems, components. To begin this process it is useful to utilize one or more creativity sessions with all or parts of the team members to identify aspects of the system to be designed, sub-systems, components, potential concerns, etc. Various creativity models can be used, for instance brainstorming, or any of the methods described by De Bono [1970, 1992, 1994], Fabian [1990], Plesk [1997], or dozens of others in the literature. Table 2 indicates a list generated during such a creativity session for the fuel cell powered SUV. One session will not likely produce an exhaustive list. Once an initial list is developed, each item should be critiqued, duplicates should be combined, and extraneous items should be deleted. For small and medium size projects, this list can be maintained on large sheets of paper and the entire team can simultaneously participate in the development process. For large projects, a computerized list will be necessary and creativity sessions may be limited to smaller sub-sets of the team; however, all team members should participate.

Decomposing the overall system begins with developing the list of components, sub-systems, concerns, etc. as described above and continues with the organizing of the list into a hierarchical structure. The topics on the list should be correlated by relationships. The more encompassing sub-systems should be identified and then the topics within each upper sub-system must be correlated and organized similarly.

Table 3 provides a possibility for the first tier of subsystems related to the development of the fuel cell SUV. The six sub-systems listed in Table 3 indicate the primary systems to be required for vehicle operation. Of course other variations could have been tried. For example, the high and low voltage systems could be lumped together as the electrical system or the control system could have been split and included partly in the fuel cell system and partly in the power train. Frequently, the first arrangement may not be best. In fact it may be necessary to organize the next level, or levels, of sub-systems under each of the blocks in the first tier. Similarly, each tier of the structure may change after possible scenarios for the previous tier are considered.

Interactions between sub-systems, components, etc. should be noted on the hierarchical structure. Indeed, there will likely be several interactions or linkages that horizontally connect sub-systems on different vertical legs of the structure. Such cross-linkages are extremely important to identify and include. The organizational process, which will be iterative at each step, must be repeated until all levels of subsystems are identified. We emphasize that there are many potential hierarchical structures that could be developed for a system; a part of the iterative procedure is to consider several possible structures in the process of developing the best structure. A schematic diagram of a typical hierarchical structure for a system is shown Figure 1. Note the gray lines which indicate an interaction between sub-groups in different vertical parts of the structure. The mindmapping process as described by Wycoff [1991] and others is a good model for a tool to help with the decomposition and organization of project. The graphical representation inherent in the mindmapping process clearly shows both the hierarchical structure and the interactions among sub-systems and components. Traditional mindmapping works well for small and medium size projects where the entire map can be displayed on a single large sheet of paper. At least one software package, Inspiration® from Inspiration Software, Inc., which supports mindmapping is widely available.

The organizational process is continuous in nature. First, it is likely that additional items will be added to the initial list as the process progresses. Additional items will be recognized as part of the organizational process because the very efforts that are needed to organize the list will help clarify understanding of the system and provide additional insight. Secondly, as the project develops additional information will be discovered and additional sub-systems, components, etc. will be identified. Further, additional and more involved interactions or linkages between various sub-systems will be realized. The organizational structure being developed must be expanded to include these new components and interactions. Thus, the task of
Table 2  Typical Components, Sub–systems, etc. Required for Fuel Cell Vehicle.

<table>
<thead>
<tr>
<th>Fuel cell stack</th>
<th>Air humidifier</th>
<th>Sensor monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traction motor(s)</td>
<td>Humidity sensors</td>
<td>De-ionized water storage</td>
</tr>
<tr>
<td>12 volt components</td>
<td>Pressure sensors</td>
<td>Radiator</td>
</tr>
<tr>
<td>High voltage battery pack</td>
<td>Temperature sensors</td>
<td>Cooling water pump</td>
</tr>
<tr>
<td>Hydrogen humidifier</td>
<td>Vehicle controller</td>
<td>Compressor cooling</td>
</tr>
<tr>
<td>12 volt battery</td>
<td>Stack preload pressure</td>
<td>Humidification water heater</td>
</tr>
<tr>
<td>Water injectors</td>
<td>Air exhaust</td>
<td>Air plumbing</td>
</tr>
<tr>
<td>Cell voltage monitoring system</td>
<td>Hydrogen storage tanks</td>
<td>Power steering</td>
</tr>
<tr>
<td>Hydrogen sensors</td>
<td>Hydrogen plumbing.</td>
<td>Power brakes</td>
</tr>
<tr>
<td>Hydrogen exhaust</td>
<td>Air filtering</td>
<td>Motor controllers</td>
</tr>
<tr>
<td>Battery monitoring</td>
<td>Compressor</td>
<td>Stack cooling</td>
</tr>
<tr>
<td>Humidifier drains</td>
<td>Hydrogen flow control</td>
<td>Air conditioning/heating</td>
</tr>
<tr>
<td>Instrumentation for driver</td>
<td>Energy management</td>
<td>Fuel efficiency</td>
</tr>
<tr>
<td>Vehicle parking control</td>
<td>Gearbox(s)</td>
<td>Reactant metering</td>
</tr>
<tr>
<td>Reactant pressure control</td>
<td>Packaging</td>
<td>Gear reducer(s)</td>
</tr>
<tr>
<td>High voltage wiring</td>
<td>Low voltage wiring</td>
<td>Sensor/actuator wiring</td>
</tr>
<tr>
<td>Fuel cell control</td>
<td>DI water filter(s)</td>
<td>Reactant humidification control</td>
</tr>
</tbody>
</table>

Fig. 1  Possible Hierarchical Structure for Fuel Cell SUV Development.
organizing and fully understanding the system being designed into is not completed until the design process is completed.

Parallel with the decomposition process should be a team member organizational process. The team for a large project is likely to be large. Thus, the structure and communication within the team and sub–teams is critical. The project organizational structure should clearly indicate the major areas of work and the important interactions among sub–systems, hence, members of the design team should be grouped into sub–teams similarly and the project organization should be reviewed frequently to ensure that no aspects of the overall design slip by.

In any endeavor that requires effective coordination of the effort of many people leadership and management are critical issues. The leader must provide vision, inspiration, and resources for the team and the leader must remove obstacles which limit the efforts of the team. The vision for the project, major resources, etc. are provided by the official team leader, however, team members must provide leadership with respect to specific efforts of the team or sub–teams. Clearly, effective team management is also important, but management is not leadership.

The working environment for the design team is important. Appropriate space and communication capabilities must be available. In earlier times, space meant a situation room with ample table space, means to display information on a scale that provides easy access, and secretaries or computer terminal operators to record activities. Today, team members may be located remotely all over the world. Work space probably refers to computer input software, display, and storage while communication is related to interactive computer sessions, e-mail, on–line conferences, other machine interfaces, and perhaps even telephone discussions. What is important is convenient communication among team members with easy transmission of data to each other and the capability to display data and ideas as structured images.

7. Conclusions

The harnessing or management of complexity requires an overt, integrated mode of operation that accomplishes the following.

- Develop a strong and well organized team.
- Recognize that large–scale systems are complex and significant effort must be directed toward reducing this complexity.
- Recognize that large–scale systems typically have a hierarchical structure.
- Decompose the system to be designed in terms of its hierarchical structure.

<table>
<thead>
<tr>
<th></th>
<th>Power train</th>
<th>Drive motors and associated components</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Fuel cell system</td>
<td>Stack, compressor, humidifiers, sensors, etc.</td>
</tr>
<tr>
<td>3</td>
<td>High voltage system</td>
<td>300 V battery pack, mounting, interface to fuel cell, etc.</td>
</tr>
<tr>
<td>4</td>
<td>Low voltage system</td>
<td>12 V electrical system to run vehicle lights, accessories, etc.</td>
</tr>
<tr>
<td>5</td>
<td>Control system</td>
<td>Fuel cell monitoring &amp; control, vehicle control</td>
</tr>
<tr>
<td>6</td>
<td>Accessories</td>
<td>Power brakes, power steering, air conditioning, etc.</td>
</tr>
</tbody>
</table>
• Identify interactions among sub-systems and components.
• Continually update the system structure to incorporate new information and changes in requirements, resources, etc.
• Identify and provide tools needed by the design team, especially for communication, manipulation and display of data and information.

There is no magic process that can remove complexity from a large-scale design process; however, good leadership, management, organization, and communication can provide a design team the ability to harness the complexity and complete a good design.

8. References
Miller, G, 1956, The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information, Psychology Review, 63(2), 81–97.