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Facilitating Learning in System Dynamics Practice

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Abstract

In SD practice our primary goal is to develop structural understanding of dynamically complex systems. Creating new understanding is a learning process defined by an improvement in people's mental models, which is consistent with modern theories of learning and instruction. With this paper, we intend to contribute to and energize a discussion in the SD community on the benefits of applying these theories to achieve our primary goal through improving mental models.

Our HOLICS workshop teaches personal energy management principles. A prototype interactive learning environment, based on a SD model integrating Jack Homer's worker burnout model with a project management model, facilitates it. To strengthen the workshop's learning impact, we developed and applied to its design a framework of learning and instruction theories. In this paper we demonstrate the application of our framework, and suggest how it could be generalized to, and therefore benefit, various forms of SD practice.

Key Words: mental models, learning theories, instructional design, learning environments

1 Introduction

We are not the first to articulate the idea that system dynamics practice can be improved by more explicit knowledge and application of learning and instructional design theories.

> "That these learning theories are reasonably well established and articulated but have not been embraced by the system dynamics learning community is somewhat disturbing." (Davidsen et al. 1999, p. 3)

We think there is an opportunity for all system dynamics interventions, not just those defined for learning, to benefit from these learning theories. As described in this paper, improving mental models *is* 'learning' and this learning is required in all system dynamics practice, even interventions designed to resolve a problem or select a strategy. The springboard for our thinking was our coursework in interactive learning environments with Professor Pål Davidsen at the University of Bergen, Norway.

Additionally, his articles on the graduated complexity principle and instructional design for interactive learning environments have encouraged us to explore our ideas further, and contribute to the "ongoing discussion regarding how to learn from using system dynamics." (Davidsen et al. 1999, p. 9)

In fulfilling our requirements for advanced degrees in system dynamics, we were given the opportunity to build an interactive learning environment on an established model. We found ourselves intrigued by the work of Jack Homer on worker burnout (Homer 1985). It appeared that the non-intuitive conclusions he drew could be important to the quality of life of a great number of people in the working and academic world. Yet we felt that the worker burnout model needed a context in which these non-intuitive conclusions could be demonstrated effectively. We chose to develop our interactive learning environment in the context of project management. We felt that discovering the contribution of worker burnout to the failure of projects would have a powerful effect on the learners (in this case, high achieving professionals and their management). Therefore, we developed a simulation model that integrated the worker burnout model with some traditional project management models.

Using this model as a base, we developed both an interactive learning environment[1] and a workshop, called HOLICS, which together teach personal energy management principles. In conjunction, we developed a learning and instructional design theories framework (referred to as our 'learning framework') by selecting the current learning and instructional design theories most relevant to our system dynamics-based workshop. This learning framework played an important role in the design of both the HOLICS workshop and the interactive learning environment.

In this paper, we suggest why and how system dynamics practice in general can benefit from the application of current learning and instructional design theories. We present our learning framework and illustrate with specific examples its application to the HOLICS workshop design. Our current discussion is theoretical and is founded on established and tested learning and instructional design theories. We see the discussion as an important starting point to further develop and apply the proposed learning framework to benefit system dynamics practice in general. We conclude the paper by identifying four specific suggestions for improving system dynamics practice.

2 Design of a Learning Intervention

2.1 How do we design an intervention to effectively and efficiently improve mental models of dynamic systems?

> "System dynamics models have little impact unless they change the way people perceive a situation." (Forrester 1991, p.16)

To improve the performance of an important dynamic system, our aim in system dynamics practice is to improve people's mental models of that system (Doyle et al. 1996, Richardson et al. 1994, Vennix 1996, Andersen et al. 1997, Doyle and Ford 1998). The mental models we hold express our understanding of reality and as such are the basis for our actions. Most importantly to system dynamicists, they are the basis for

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[1] We use the term 'interactive learning environment' to refer to the system dynamics-based software application that facilitates the HOLICS workshop. Different authors have referred to these software applications in various other ways, including terms such as: 'games', 'management flight simulators,' 'virtual worlds,' or 'system dynamics-based interactive learning environments'. Maier and Größler (2000) provide a comprehensive review of terms in use.

designing new policies to modify system structure and improve system performance. Improving mental models is difficult under any circumstances, but the complexity of the systems we explore with system dynamics makes becoming aware of and improving mental models even more difficult. Although system dynamics practitioners aim at improving mental models, we have not yet clearly identified the most effective and efficient methods to achieve this.[2]

When we began to design the HOLICS workshop, the questions we kept returning to were:

> *How do we design the workshop so it gives participants an appreciation of the worker burnout problem and its dynamic nature? and*
>
> *How do we effectively improve their mental models so they manage their personal energy to avoid worker burnout?*

We realized that system dynamics models and causal loop diagrams, although valuable, were not sufficient to ensure the success of the workshop. What we additionally had to do was design the workshop to be an integrated learning process during which workshop participants would be introduced to the worker burnout problem and would improve their mental models of project management and personal energy management, i.e. would learn the concepts we wanted them to learn in an effective and efficient way.

Having been exposed to some learning and instructional design theories during our university course, we recognized these fields as valuable sources of insight and guidance in our efforts to design the learning process of our workshop. Based on our further research, we identified and selected the theories and practices most relevant to our workshop. From this selection we formulated the following framework of learning and instructional design theories, which we applied to the HOLICS workshop design (see Figure 1):

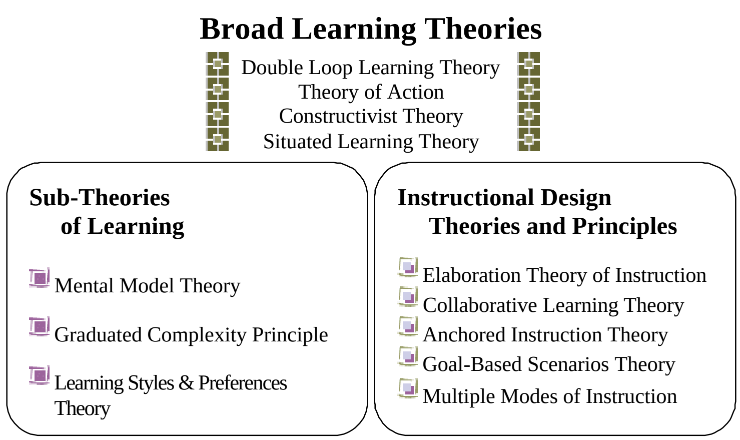

Figure 1 Schematic representation of our learning framework

We demonstrate the application of these theories to the design of the HOLICS workshop in detail in the next section, Section 3. The remainder of this section is devoted to a short description of the learning and instructional design theories included in the framework and their relationship to system dynamics. *Learning theories* define *how people learn*, while *instructional design theories* define *how people should be taught.* First, we describe the theories on what motivates learning. A learner must be motivated before they will make the effort to learn something new. Second, we describe the theories that are consistent with system dynamics philosophy. These theories are fundamental to the reconstruction of mental models and the acquisition of knowledge for those mental models. Next, because

[2] See discussion on Andersen et al. 1997 in Section 4.

our workshop is concerned with a dynamically complex system, we include a section on the learning theory that addresses complexity. Finally, since our workshop is a group-based process, we discuss the theories that address learning in a group.

2.1.1 Motivators for Learning

* Double-Loop Learning Theory * Theory of Action *

People take action in the world to obtain the results they desire. When there is a mismatch between the results they achieve and the results they expect, they are motivated to find out why and therefore to learn. Once they (believe they) know why their past actions were unsuccessful, they take new actions in an attempt to again achieve the results they desire. Until there is a match between results and expectations, this cycle continues.

In complex systems, there are three important reasons why results mismatch with expectations. First, we often misperceive feedback from our actions, so we cannot easily learn the correct reasons our results do not match our expectations. [3] This can keep us in a never-ending cycle. Second, there can be a difference between how the world works and how we think it works. If we act upon an incorrect understanding of the world, our actual results are likely to be different than our expectations. Third, there is often a difference between what we say or think we will do, and what we actually do. If expectations are based on what we think we will do, and yet we actually behave differently, our results will mismatch our expectations. These last two reasons for a mismatch are addressed by two learning theories, the double-loop learning theory and the theory of action.

In their double-loop learning theory, Argyris and Schön (1978) distinguish between two types of learning that produce different changes in action in people's effort to improve results:

1) 'Single-loop learning' takes place when people change their actions without changing their beliefs about the way the real world works. For example, using the same strategy for accomplishing results, just changing the effort or resources invested.
2) 'Double-loop learning' takes place when people change their actions as a result of changing their beliefs about the way the real world works. For example, completely changing the strategy to be used for accomplishing results.

Argyris argues that to ensure successful performance of any organization, any system, double-loop learning must occur. Yet, single loop learning is much more common. (Argyris 1991)

In their earlier work Argyris and Schön (1974) formulated the theory of action, where they distinguished between 'espoused theories' and 'theories-in-use'. Espoused theories are what people say they do or think they do, while theories-in-use determine their

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[3] The cognitive limitations of humans were thoroughly investigated by cognitive scientists beginning with Miller's (1956) definition of the 7 +/-2 temporary memory capacity. Research within the German school, led by Dörner and associates, is the most relevant to system dynamics as it documents human limitations in the perception of feedback and delays, which contribute to the problems people have managing complex systems (see e.g. Dörner 1989, Funke 1991). Experimental work done by Sterman and others confirms these findings in the system dynamics context (see e.g. Sterman 1989, Kleinmunts and Thomas 1987, Paich and Sterman 1993).

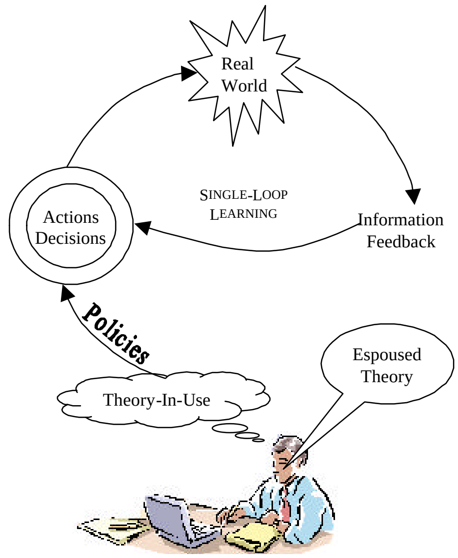

Figure 2 Single-loop learning

actions, or behavior. In system dynamics we define a mental model as *the understanding of the real world that determines people's behavior*. Therefore, people's theories-in-use are the same as their mental models. Typically only the espoused theories are explicit and the theories-in-use remain tacit, therefore the differences between the two are often unseen. Figure 2 illustrates single-loop learning, which is characterized by the lack of connection between espoused theories and theories-in-use, and the inability of information feedback from the real world to influence these theories.

For double-loop learning to occur several things must happen. First, people must determine what their current mental model of the system is. This requires them to make their theories-in-use conscious. In doing so, any discrepancies between what they actually do and what they claim to do are identified. Second, once their mental model has been surfaced, it is evaluated for its accuracy in representing the real world. This is achieved by comparing both structure and behavior: how does the mental model compare with other people's mental models, and how does their mental model behavior compare with real world behavior. Both of these comparisons identify discrepancies in people's mental models that need to be explored. (The behavior comparison must usually be done with computer simulation, as human cognitive abilities are limited for determining behavior from mental models without assistance.) Third, an improved mental model becomes the basis for future actions. The theories-in-use and espoused theories must converge, as only through communicating and acting upon a single understanding of reality will it be possible for people's results to meet their expectations. Figure 3 illustrates the double-loop learning theory.

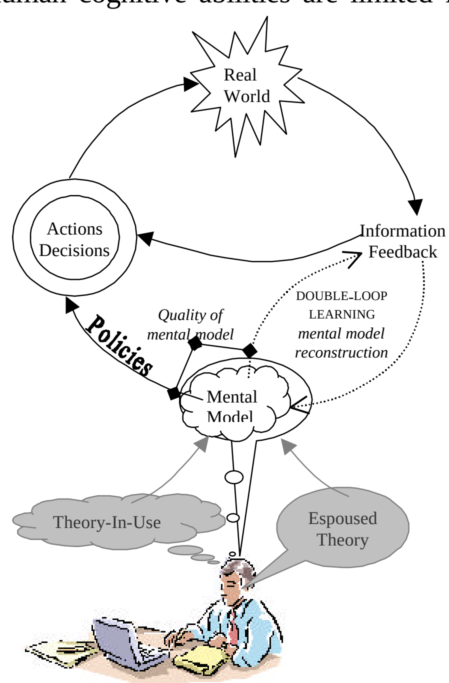

Figure 3 Double-loop learning

Most often people dealing directly with the problem situation do not see the necessity for double-loop learning and search only for single-loop learning fixes. Therefore, an intervention with the goal of producing double-loop learning must first motivate that learning. It should begin by raising the awareness of the learners to important discrepancies between their espoused theories and theories-in-use, their mental models and those of others, and their expected and actual performance based on these models.

System dynamics is an excellent method for raising awareness in these areas and facilitating double-loop learning:

1) **Learner espoused theories and theories-in-use**.
   Developing a system dynamics model relies on eliciting mental models (i.e. theories-in-use). Hence, in a successful system dynamics intervention, identification of any possible discrepancies between the espoused theories and theories-in-use is unavoidable. Typically initial models are based on people's espoused theories - what they think they do. Slowly it becomes clear, through discussion and comparison of structure and behavior, what the actual mental models are - the theories-in-use. The discovery of the discrepancies between these theories causes confusion and frustration (Campbell 2001). While this is probably the most difficult part of the intervention, it may also be the most valuable since it motivates double-loop learning.

2) **Learner mental models and those of others.**
   During the system dynamics model-building process mental models of various actors involved in the system are shared, explored, and challenged by others. During this process, mental model structure is validated, and a shared and improved mental model is created.

3) **Learner expected and actual performance based on these models**.
   Building and simulating system dynamics models allow us to assess the accuracy of people's mental models (already improved from the above double-loop learning process steps). As indicated previously, people often inaccurately predict the behavior of complex systems and misperceive the reason for that behavior. Using simulation models of the complex system can reduce these problems. Working with models based on their own mental models, learners can analyze the cause of the mismatch between their expectations and actual results. As the simulation models represent the learners' mental models, the simulation results can be compared with historical, real-world results to determine whether the mental models accurately describe the real system. Additionally, if their mental models appear from this comparison to be correct, learners can then compare these simulation results with their own expectations, to determine if they are able to accurately 'simulate' their mental models in their heads. If their mental models are correct, they may still be unable to predict the final result due to human cognitive limitations.

System dynamics simulation models offer 'virtual worlds' that motivate and accelerate double-loop learning. Interactive learning environments - system dynamics models with user-friendly interfaces - are especially effective in motivating and accelerating learning in and about complex systems (Sterman 1994, Lane 1995, Davidsen 1996). Our HOLICS workshop employs this type of interactive learning environment. The overall learning environment created during our workshop, with the use of the interactive learning environment, closely represents the real world and teaches an approach to thinking useful in the real world.

2.1.2 Learning as Knowledge Organization and Knowledge Acquisition

Learning theories typically address both the organization and acquisition of knowledge, but often emphasize one or the other. Therefore, in presenting the theories, we have divided them into these categories. With each learning theory, we have associated related instructional design theories where appropriate.

Learning as Knowledge Organization

* Constructivist Theory * Mental Model Theory * Elaboration Theory of Instruction*

In the cognitive science field, there are multiple theories on how the knowledge we apply in reasoning and problem solving is structured (see e.g. Galotti 1999 for a comprehensive review). In system dynamics we call these cognitive structures 'mental models'. This is consistent with the **mental model theory**, which also states that the basic cognitive structure underlying people's understanding and facilitating their actions is expressed in the form of a mental model. Johnson-Laird (1983) is a major proponent of the mental model theory. He argues that mental models are fundamental cognitive structures that facilitate all human cognition processes, including problem solving, reasoning, critical thinking, and decision making. This learning theory is fundamental to our workshop design.

The other learning theory fundamental to our design due to its emphasis on developing cognitive structure is the **constructivist theory** of Bruner (1960). In the constructivist perspective, learning is the process of reconstructing the cognitive structures that represent our understanding of a particular domain. Many constructivists also refer to these cognitive structures as mental models:[4]

> "Constructivism is a philosophy of learning founded on the premise that, by reflecting on our experiences, we construct our own understanding of the world we live in. Each of us generates our own 'rules' and 'mental models,' which we use to make sense of our experiences. Learning, therefore, is simply the process of adjusting our mental models to accommodate new experiences." (Funderstanding 1998, http://www.funderstanding.com/learning_theory_how1.html, accessed January 2001)

In the constructivist theory, learning is an active process during which the learners themselves construct new concepts. The development of the appropriate mental model to represent this new concept is a prerequisite for the successful performance of a learner. Constructivists also advocate iterative learning. Bruner (1966) indicates that instruction leading to a successful change of mental models should be based on a *spiral curriculum*. It should begin with the learner's current understanding of the domain to be learned, and gradually incorporate new knowledge over the course of the instruction. Reigeluth and Stein (1993) further develop the spiral curriculum concept in their **elaboration theory of instruction**. They emphasize that learning is a gradual process and takes place as a result of the repeated elaboration of concepts.

These theories advocate that the fundamental concepts in system dynamics are fundamental concepts to learning: 1) mental model reconstruction, which results from involvement in the system dynamics model-building process and/or experimentation with the model (see e.g. Forrester 1991, Sterman 1994, Davidsen 1996, Doyle and Ford 1998), and 2) iteration, which all system dynamics researchers and practitioners emphasize is the nature of the system dynamics process (see e.g. Randers 1980; Richardson and Pugh 1981; Vennix 1996; Sterman 2000).

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[4] See also Jonassen 1998 and Seel 1999

Learning as Knowledge Acquisition

* Situated Learning Theory * Anchored Instruction Theory * Goal-Based Scenarios Theory of Instruction *

The **situated learning theory** (Lave 1988) advocates embedding learning into an environment that closely resembles the natural environment where acquired knowledge is to be applied. According to this theory, learning is accelerated when the learning context represents a real-life situation. Situated learning draws on the results of research conducted in the cognitive science field illustrating how people's performance changes depending on the context in which they are required to carry out a task. For example, Galotti (1999) refers to research by Carraher and associates, where it is shown that Brazilian children working as street vendors score 98% correct on responses when asked questions such as "If a large coconut costs 76 cruzeiros, and a small one costs 50, how much do the two cost together?"[5], but give correct answers only to 37% of questions formulated as "How much is 76+50?"[6] Bransford and Stein (1993) developed the **anchored instruction theory** advocating that instructional design should be guided by the specifics of a real-life situation in which the new knowledge is to be applied. Schank (Schank et al. 1994) takes a similar stand in his **goal-based scenarios theory of instruction.** He advocates that learning should be action-based, that learners not only need to apply their new knowledge in a real-life context, but must also mimic the actions they would take in doing so - they should 'learn-by-doing.'

As was indicated previously, system dynamics simulation models play an important role in the reconstruction of mental models and acquisition of new knowledge. They allow a learner to apply new knowledge in settings that are close to reality, yet stripped of its hazards. In a safe environment, the learner has a unique opportunity to develop and easily test improved mental models of the real system (Senge and Sterman 1994). In our HOLICS workshop we create a learning environment in which the learners can experiment. This helps them improve their mental models (their understanding of the real system). They can also design and test their improved policies and, based on this experience, implement the most successful ones in real-life. Indeed, our workshop facilitates 'learning-by-doing' in an almost 'real' context.

2.1.3 Learning about Complex Systems

* Graduated Complexity Principle *

When dealing with complex problems and systems it would hardly be possible or effective to create a learning environment that replicates the real system. Hence, an effective intervention creates a learning environment that closely resembles a real-life situation, but by no means tries to mirror it. In our workshop we developed this type of learning environment based on a system dynamics model. Any system dynamics model, although a simplification of reality, may still be relatively complex and difficult to comprehend. Therefore, it was crucial that we adhered to the **graduated complexity principle** (Spector and Davidsen 1998). This principle articulates the need for a highly complex subject to be taught in a progression from "the relatively simple to the more complex." (Davidsen et al. 1999, p.4)

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[5] Quoted from Galotti 1999, p.581

[6] Ibid.

2.1.4 Learning in a Group

* Collaborative Learing Theory of Instruction * Learning Styles and Preferences Theory * Multiple Modes of Instruction *

We chose to make our workshop a group-based intervention for two important reasons: first, because becoming aware of and improving mental models is accelerated when working in a group, and second, because the **collaborative learning theory of instruction** (see Jonassen 1998) emphasizes that learning is improved through social interaction. Since the workshop is group-based, to ensure that all participants benefit from and contribute to the process equally, it is important that individual differences are taken into account. Therefore, we guided our design with the **learning styles and preferences theory**:

> "[The learning styles and preferences theory is] based on research demonstrating that as the result of heredity, upbringing, and current environmental demands, different individuals have a tendency to both perceive and process information differently." (Funderstanding 1998, http://www.funderstanding.com/learning_theory_how6.html, accessed January 2001)

This theory indicates that different people, depending on their individual predispositions, learn most effectively in different instructional settings (Morgan 2000).

Additionally, different modes of presentation are more effective with different individuals. Therefore, when designing our group-based workshop we chose to also use **multiple modes of instruction**. Audio, visual and 'action' modes are the most fundamental ones. By using multiple modes of instruction we increase learning. Research results indicate that the three modes of 'listen, see, and do' produce an average learning success rate of 70%, whereas the two modes of 'listen and see' produce an average success rate of only 40%. All three theories relate to system dynamics practice, especially to system dynamics group-based practice, i.e. group-model building and workshops where learning is done in groups.

2.2 The learning framework revisited

A general overview of our learning framework was presented in Figure 1. We summarize the above discussion by presenting our learning framework once more, emphasizing its relationship to double-loop learning, in Figure 4.

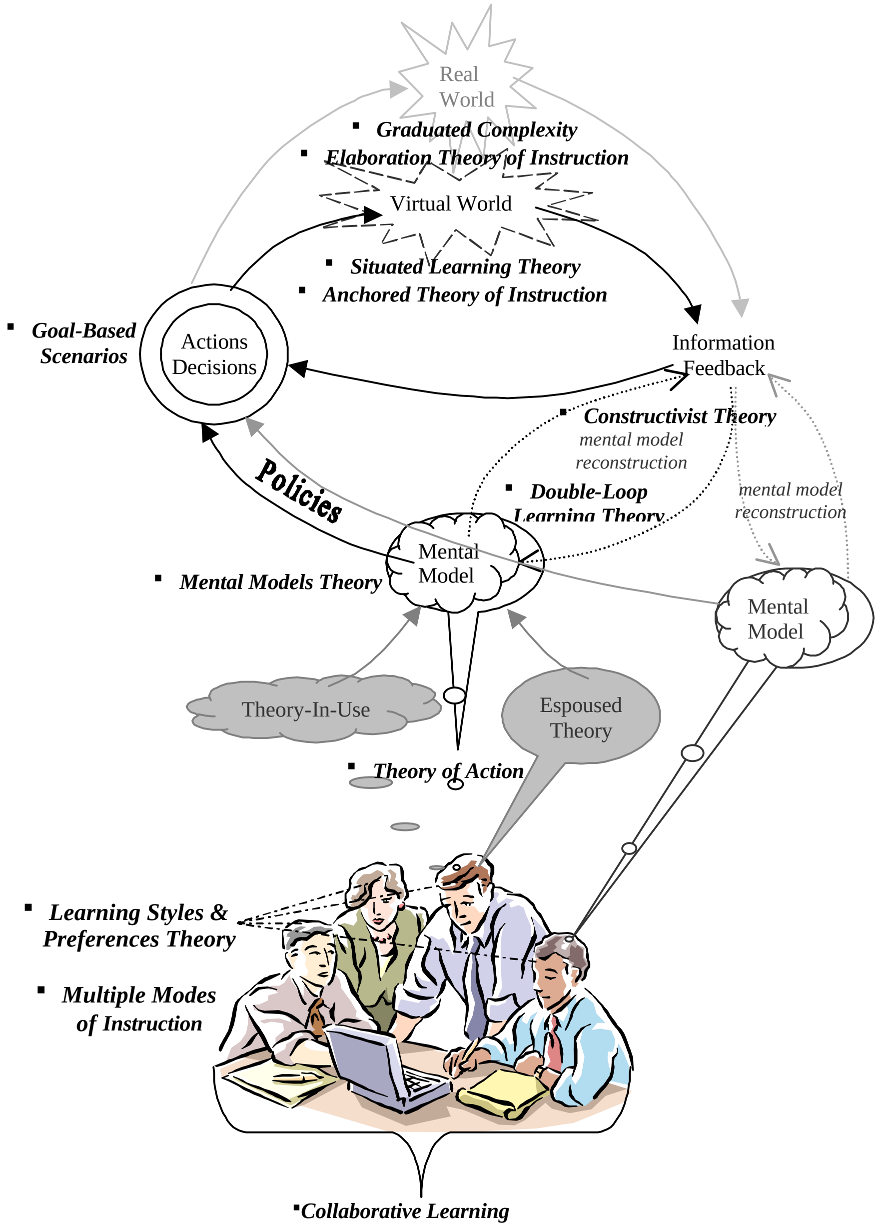

Figure 4 Overview of the learning and instructional theories framework for HOLICS workshop

3 Critical Assessment of the HOLICS Workshop

In this section, we demonstrate how we applied our learning framework to the HOLICS workshop design. First, we briefly describe the HOLICS workshop. Next, we present the four learning goals defined for HOLICS. Then, we discuss how we applied each of the learning and instructional design theories included in our framework to facilitate the learner's accomplishing the learning goals. In this discussion, we describe first how the learning theories were applied, and second how the instructional design theories were applied to the workshop design. By applying learning and instructional design theories, we created a more effective interactive learning environment and workshop. The time in the workshop is used only on activities that support sharing, reconstructing, and improving the learners' mental models, and achieving consensus and commitment to the resulting strategies. To do so we used theories of motivation, knowledge organization and acquisition, and complexity. We conclude the section by identifying areas of the workshop that require improvement.

3.1 Workshop Description

High achieving individuals have high expectations for their personal performance. As a result they place demands on themselves that can lead to low productivity due to the personal energy loss caused by stress and long work hours. In business, this low productivity can result in missed deadlines and lost profits (Homer 1985). The HOLICS workshop raises the awareness of high achievers to the contribution their personal expectations make to their productivity loss, and teaches them ways to manage both their expectations and personal energy to achieve higher productivity.[7]

The HOLICS workshop is designed for teams of participants. Each team's mission is to complete seven subsequent independent projects within 6 months each, and keep their quality of life indicators high.[8] Each project begins with a team meeting. During this meeting, a plan for completing the project is made, and individual participants commit to the number of accomplishments they will achieve in the first month. Then participants return to their work desks and provide individual weekly estimates of the number of accomplishments they will complete, and the number of hours that will be required, to the interactive learning environment. During the course of the simulation, participants follow both their individual performance and the project progress. After one month elapses in the simulation time, there is another monthly meeting where the status of the project is discussed and a plan for the next month is determined. This process continues until the project is successfully completed or unsuccessfully terminated. At the completion of each project a full debrief with the workshop facilitator is conducted and important newly learned concepts are reinforced.

3.2 Definition of Learning Goals

The primary purpose of the HOLICS workshop is for the learners to attain higher personal productivity and more consistent project completion success. In the context of this purpose, we identified the following learning goals that should be achieved at the completion of the workshop. By developing learning goals, we designed a more focused interactive learning environment and workshop.

1st goal: Participants know key systems thinking principles:

a. Structure drives behavior
b. A change in behavior of the system requires a change in structure

Additionally, participants know causal loop diagram notation.

2nd goal: Participants understand the high and low cycles of productivity in high achievers and the structure underlying these dynamics, including:

a. The impact of personal expectations
b. The impact of personal energy level

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[7] Some psychological pre-tests should be conducted to find out whether each participant has a high achievers personality (Psychological Test Resource, accessed March 2000).

[8] There are three main life quality indicators: Personal Well-Being (describes the overall well-being and life quality), Relative Work Success (describes individual's work performance in relation to other team members), JERK quotient (keeps track of individual's social image).

3rd goal: Participants are able to increase performance on the job by improving their time and accomplishment estimation strategies.

4th goal: Participants are able to increase performance on the job and the quality of their personal life by improving their personal energy management strategies.

These learning goals are met as a result of the learning process that takes place during the HOLICS workshop.

3.3 Application of Learning Theories

Since all the learning theories included in our framework facilitate the learning in our workshop, they all apply and contribute to achieving the learning goals. However, the extent to which each of the theories contributes to achieving various learning goals is different. For each learning theory, we describe how it was applied to the learning goal it contributes to the most. The exception is the double-loop learning theory, which applies to the overall design of the workshop and is presented first. The 3rd and 4th learning goals are addressed jointly, since they are achieved using the same learning theories.

3.3.1 Application of the Double-Loop Learning Theory

Problems encountered by the HOLICS workshop participants closely resemble the situations they face in their every day life. In this 'virtual world' learning environment, workshop participants learn about various aspects of personal energy management (see Appendix 1). They apply their knowledge when making their individual decisions about the number of tasks ('accomplishments') they wish to complete in the upcoming time period ('a week' or 'a month') and the number of hours they wish to devote to these accomplishments. Their decisions are supported by the HOLICS interactive learning environment, which simulates the individual's and team's efforts in conducting several product development projects in succession.[9] The 'actual' results together with the participants' earlier estimates are reported back after each decision is made. In that way, participants constantly verify their 'actual' accomplishments against their estimates. Additionally, each individual's decisions and strategies are discussed during the debriefing sessions, allowing for an explicit and in-depth analysis of them.

Mistakes made in this virtual environment, unlike similar mistakes often made in reality, are much easier to detect. (And of course are 'reversible' and cannot cause any real damage.) The workshop facilitates a constant, in-depth examination by the learners not only of their practices, but also of their mental models, allowing them to identify possible inconsistencies between their espoused theories and theories-in-use. In that way, mental models are improved and they in turn facilitate the discovery and implementation of effective personal energy management strategies on the job. Having learners apply new knowledge in a way that challenges their mental models and leads them to reconstruct and improve their mental models is consistent with the **double-loop learning theory** (see subsection 2.1.1).

[9] In the current version of the HOLICS workshop, materials are tailored to support a series of product development projects in a high technology company context. If the workshop is to be conducted with participants of a different background, all context-dependent material (e.g. verbal description of the project and team-members roles, references to real-life cases) can be appropriately updated.

3.3.2 Application of Other Learning Theories to Specific Learning Goals

1st goal: Know systems thinking principles

* Situated Learning Theory *

We identified two crucial systems thinking principles to be learned by the workshop participants: the principle of system structure driving system behavior, and the principle that the only way to influence system behavior is through a change of system structure. To facilitate this, they must also learn causal loop diagram notation. The main decision screen of the HOLICS interactive learning environment presents the system structure diagrammatically using causal loop notation. To investigate the structure-behavior relationship within the system, participants must therefore learn causal loop notation. They are introduced to the notation during the facilitator's introductory presentation (see Appendix 1). However, they are not expected to learn it right away. Instead, they are provided with a summary overview in their reference materials,[10] and expected to become fluent in reading causal loop diagrams during the course of the workshop. Throughout the workshop, participants are repeatedly exposed to information presented in the form of causal loop diagrams and must read them correctly to be successful. The **situated learning theory** (see subsection 2.1.2) advocates directly engaging learners in an activity that requires the use of new knowledge (in our case, causal loop diagram notation).

In a similar way, the workshop participants study and learn about the inter-dependence of system structure and behavior. They actively use the HOLICS interactive learning environment, which highlights the relationship between the structure and behavior of the system in its interface (see Appendix 2). As a result, they have numerous opportunities during the workshop to observe and analyze how the structure of the system influences the behavior of the system. They do this both by observing how pre-programmed changes to structure change behavior as well as how changes they make to structure change behavior. Thus the workshop participants come to know the two systems thinking principles by actively using their new knowledge, again consistent with the **situated learning theory**.

2nd goal: Understand the high and low productivity cycles of high achievers and the structure underlying these dynamics (incl. the impact of personal expectations and personal energy level)

* Constructivist Theory * Mental Models Theory * Graduated Complexity Principle * Learning Styles and Preferences Theory *

To achieve this learning goal workshop participants will develop an improved mental model of a complex system. Developing a better model will require them to reconstruct mental models they previously held. The **mental model theory** postulates that a mental model expresses one's understanding of concepts in the real world, and the **constructivist theory** postulates that 'learning' is the activity of reconstructing the mental models we hold to improve them (see subsection 2.1.2). These two learning theories therefore are the foundation for our approach to this learning goal. The

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[10] Two reference guides are designed for workshop participants. The four-page *Quick User Reference* briefly discusses the participant's role, task, and environment, giving an overview of the workshop structure and outlining the routine to follow. It also provides a one page overview of causal loop notation. Additionally, a user may refer to the two page *Quick User Guide* that describes different sections of the HOLICS interactive learning environment.

HOLICS workshop and interactive learning environment are designed to facilitate the reconstruction of participants' mental models. We know this reconstruction process is not instantaneous. Mental models are hard to alter and such change is often difficult and requires time (Campbell 2001, see also the discussion in subsection 2.1.1). This is the reason why the workshop, while addressing a relatively small complex system, is designed to take two full days covering seven consecutive projects: to allow for the time and thought necessary to reconstruct participants' mental models (see Appendix 1 for the overview of the workshop and the key concepts to be learned).

This mental model reconstruction is aided by gradually introducing new material to the learner. The gradual introduction of learning material is advocated by the **graduated complexity principle** (see subsection 2.1.3). This principle is key to developing a good understanding of the dynamic characteristics of a complex system. During our workshop, the facilitator introduces key concepts gradually through presentations given at pre-defined stages of the workshop (see Table in Appendix 1). The graduated complexity principle was not only applied to the workshop design, but also to the HOLICS interactive learning environment design. Since the HOLICS interactive learning environment facilitates the learner's decisions, it plays a central role in developing the participants' understanding of the dynamics of the system. Applying the graduated complexity principle, the interactive learning environment evolves over the course of the workshop, incorporating the new concepts learned by the workshop participants as they are learned. The gradual evolution of the interface screens is demonstrated and briefly discussed in Appendix 2.

The main HOLICS screen provides participants with the information necessary for their on-going decisions at each stage of the workshop. Here the information is provided in an 'information-push' manner – the user does not look for the information but is given it unconditionally, by 'default'. The facilitator's presentations of new concepts have the same character. Additionally, at any time during their use of the HOLICS interactive learning environment, participants can access reference sections (see Appendix 3) to study, refresh, or further develop their knowledge of the material. Since the information is delivered to a user 'on demand', it is provided in an 'information-pull' manner.

The design concept related to the 'information-pull' feature of the HOLICS interface that is especially interesting is that a workshop participant progresses to the next level of interface after they explore a new concept, even if it has not yet been covered in the facilitator's presentations. Once new information about the structure of the system and its behavior are retrieved, the main interface screen evolves to a more advanced one, providing information

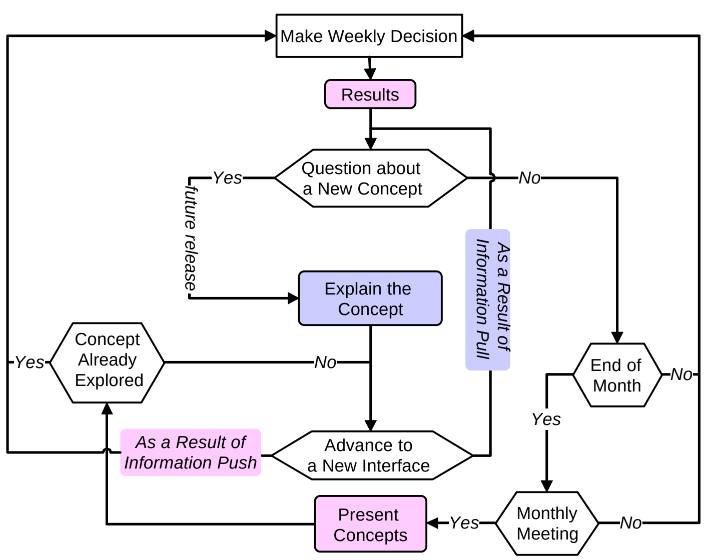

Figure 5 Flow diagram of the decision making process

to the participant at his or her new level of knowledge (see Appendix 2).[11] With each such evolution, not only the main interface screen is updated, but also the reference section screens evolve, to facilitate the exploration of new issues and the further acquisition of knowledge (see Appendix 3).[12] This information push/pull design is illustrated schematically in Figure 5.

The reference resources provided in the HOLICS interactive learning environment, as well as the documentation[13], are good examples of how participants can individually explore the learning material and/or recall the material that was presented during the facilitator presentations and group discussions. Allowing learners to explore the learning material individually, as well as in a group setting, and presenting this material in various forms, is important because of the diverse learning styles and preferences of different learners. This design is consistent with the recommendations of the **learning styles and preferences theory**. Providing learners the opportunity to explore the learning material independently of others supports an introverted learning style, while group discussion supports an extroverted learning style. By ensuring that the learning environment is not focused on or biased towards one particular learning style, we ensure that all individuals get a chance to learn in the way that is most effective for them.

3rd and 4th goals: Improve strategies of time and accomplishment estimation and personal energy management to improve performance on the job
* Situated Learning Theory * Learning Styles and Preferences *

Participants are expected to improve their estimation and personal energy management strategies during the course of the HOLICS workshop. Strategy improvement is driven by our learning process, which requires individuals to repeatedly revise and test their policies. This process – carried out in an environment that is familiar to participants and relates directly to their everyday practice – is consistent with the **situated learning theory** (see subsection 2.1.2). To ensure all workshop participants are equally motivated to improve their strategies, we implemented the **learning styles and preferences theory** (see subsection 2.1.4). Participants whose learning is motivated primarily by competitive settings are provided appropriate feedback about their performance relative to other team member's performance. For example, participants are provided a report on a 'monthly' basis that compares their accomplishments with those of their teammates (see Figure 6).

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[11] This feature is not implemented in the current version of the HOLICS interactive learning environment prototype due to technical constraints.

[12] It is important to note that the overall design of the HOLICS interface, its incremental evolution and flexibility of use, is not only consistent with the **graduated complexity principle** (see subsection 2.1.3), but also with the principles of human-computer interaction design (Preece 1994) and usability engineering (Nielsen 1993). These principles adhere to limitations of human perception capabilities and the **learning styles and preferences theory** (see subsection 2.1.4). The design and development of the HOLICS prototype was greatly eased and accelerated by applying the human-computer interaction design methods and techniques. We applied the envisioning design techniques (such as holistic design, sketching and metaphor, and scenario-based techniques) using the prototyping approach (Preece 1994).

[13] We deliberately designed extremely brief reference materials to assure that participants have easy access to crucial information. In the course of the workshop, participants will receive facilitator slide-show handouts and will be welcomed to make any notes they wish or print out copies of various reference materials provided by the References section of the HOLICS interactive learning environment.

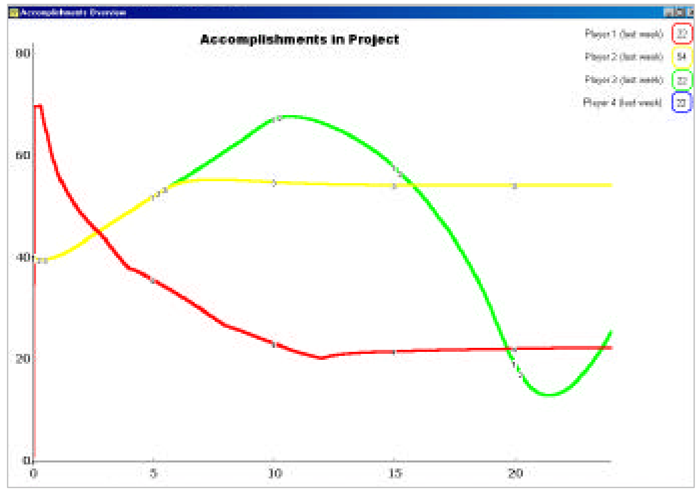

Figure 6 Example project report in the HOLICS workshop

This comparison of participant performance during the project provides strong encouragement to the competitive-oriented learners. Yet, it also provides a basis for the discussion of effective strategies and facilitates cooperative learning between teammates. Participants are encouraged by the facilitator to share and discuss their insights and experiences, and to work together during the monthly meetings. Collaboration is necessary because the success of each team member is required to complete each project on time. This collaboration motivates individuals with a cooperative learning style.

3.4 Application of Instructional Design Theories

The HOLICS workshop instructional design is based primarily on the elaboration theory of instruction. We also applied the collaborative learning, anchored instruction and goal-based scenario theories, as well as the multiple modes of instruction principle. The introduction of new concepts and knowledge to the HOLICS workshop participants does not follow a linear scheme. Instead it uses a spiral-like scheme, where none of the workshop phases addresses a particular learning goal: each of the goals is addressed by each of the workshop phases, just in a slightly different way. Figure 7 presents diagrammatically the spiral-like scheme of the HOLICS workshop. A spiral-like scheme is consistent with the **elaboration theory of instruction** (see subsection 2.1.2) and the instructional perspective proposed by Davidsen et al. (1999). The interface of the HOLICS interactive learning environment follows the spiral-like scheme of the workshop with a gradual build-up of the causal loop diagram on subsequent interface screens (see Appendix 2).

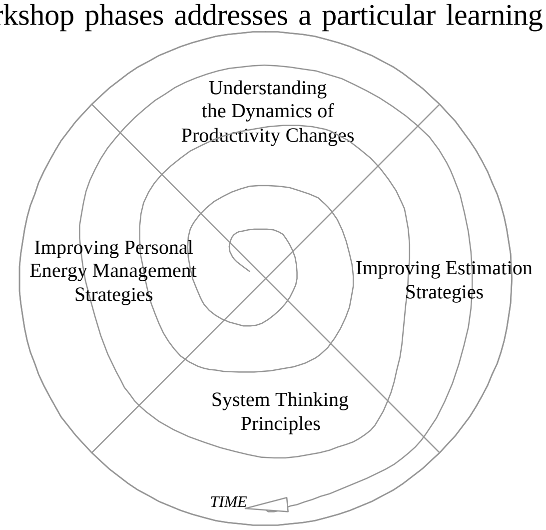

Figure 7 Spiral-like scheme for achieving the HOLICS learning goals

In the HOLICS workshop a group of four participants forms a team working jointly on projects. The team/group-based design of the workshop implements **collaborative learning** (see subsection 2.1.4). A natural collaboration in the context of project realization is established between participants: They meet at monthly project meetings to discuss project progress and their strategy for project completion. Simultaneously, each of the participants has the responsibility to make individual decisions on how much time and effort they invest each month. The problem setting is designed to mimic as realistically as possible a project situation, while remaining generic enough so the principles could be easily taught to participants with diverse backgrounds. This type of design, embedding the learning in some real-life situation that requires applying the newly learned principles, implements the **anchored instruction theory** (see subsection 2.1.2). Additionally, instruction during which participants gain knowledge not only through studying materials, or listening to various presentations, but also through actively engaging in solving problems that require applying the new knowledge is consistent with the **goal-based scenario theory of instruction** (see subsection 2.1.2).

Following the **multiple modes of instruction** recommendations (see subsection 2.1.4), our instruction is delivered to students in various modes. In the HOLICS workshop we provide instructions in all three modes. The audio mode is provided by facilitator presentations and group discussions, both formal and informal. Since presentations given by the facilitator are supported by slide shows, posters and other printed materials, they provide one form of visual mode. The individual interaction of each participant with the HOLICS interactive learning environment provides an additional form of visual mode and facilitates the 'action' mode.

3.5 Overview of Our Applied Learning Framework

A schematic summary of the way we applied the learning and instructional design theories included in our framework is presented in Figure 8.

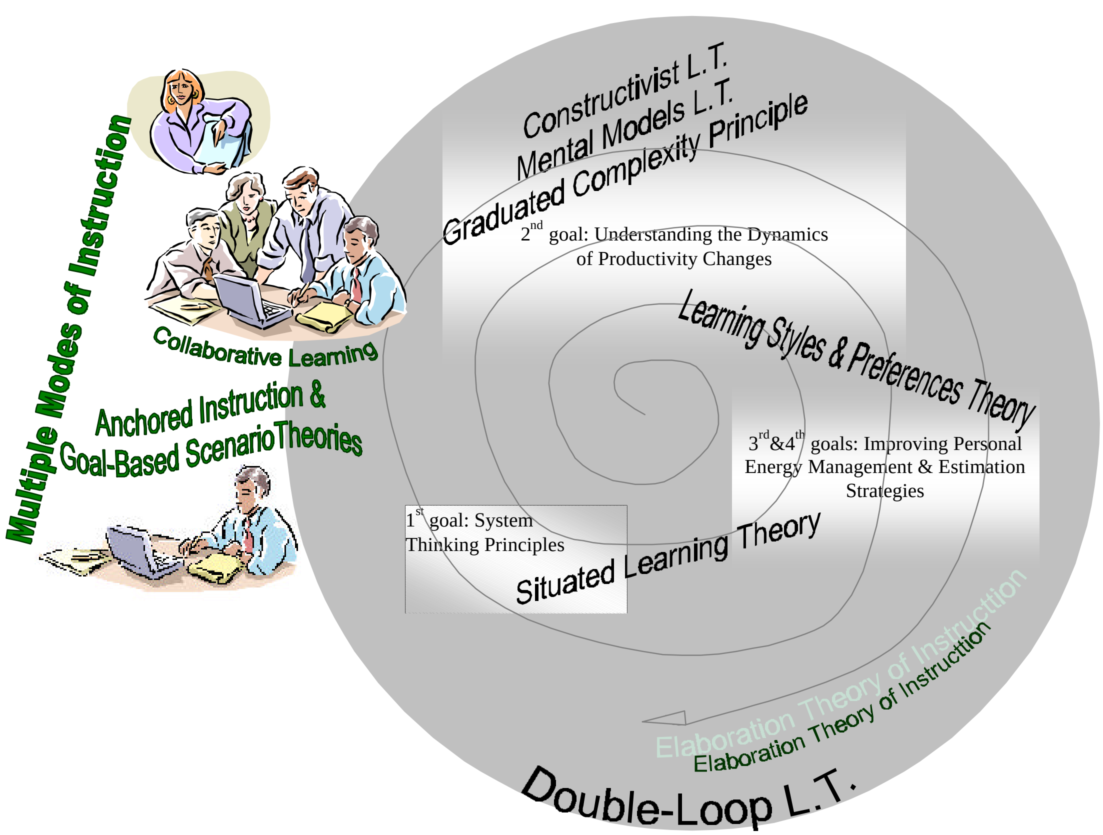

Figure 8 Application of the learning and instructional design theories in the HOLICS workshop

3.6 Areas for Improvement

Drawing from the above discussion, which demonstrates how we implemented learning theories in the HOLICS workshop to increase its ability to meet the learning goals, we have identified three major areas requiring development and improvement: goals definition, learning and instructional design theory references, and assessment tool.

1) Goals definition

During an analysis of our learning goals we discovered that assessing the achievement of learning goals becomes difficult when goals are defined broadly. We determined that both the "know systems thinking principles" and "improve estimation and personal energy management strategies" goals (see subsection 3.2) were defined at a level of specificity where assessment was relatively easy to perform. However, we found it troublesome to assess the goal "understand the dynamic cycles of productivity and the underlying structure" due to the wide scope of the goal. Therefore, it seems crucial that learning goals are formulated in a clear way and at the right level of specificity. Clear enumeration of learning goals for any particular learning intervention would also allow for positioning of an intervention in the larger matrix of educational objectives. An example of such a matrix is the educational objectives taxonomy developed by Bloom and associates (Bloom 1956, Krathwohl 1964).

2) Learning and instructional design theories references

In our opinion, repeated application of learning and instructional design theories during the HOLICS workshop design allowed us to develop a learning environment that can effectively facilitate learning about a particular dynamic system. Recognizing the important influence of learning and instructional design theories on the development of our workshop, we also recognize an opportunity to learn much more in these fields. In our opinion establishment of a closer collaboration between system dynamics practice and these research domains is important. The works of Spector and Davidsen 1998, Davidsen et al. 1999, Christensen et al. 2000 are good examples of such collaboration. This type of collaboration should not be seen only as an opportunity to improve system dynamics practice. In the field of cognitive science it has often been emphasized that it is difficult for people to learn about complex, ill-structured domains. Yet, the field seems unable to provide a consistent and general enough method that could facilitate the solving of complex problems. Therefore, a collaboration between the system dynamics and cognitive science fields could result in cognitive scientists recognizing system dynamics as a method able to facilitate and support complex problem solving and learning in and about ill-structured domains.

3) Assessment tool

In this section we have theoretically assessed the ability of our HOLICS workshop to provide an effective learning environment. One of the major shortcomings of the workshop is its lack of learning assessment tools. The one formal evaluation that was conducted was an evaluation of the instructional design of the workshop. This evaluation was based on the framework developed by Gagne (1985). The assessment indicated that the workshop meets all criteria defined by Gagne to ensure that the instructional design will successfully facilitate learning. In the system dynamics literature we find a number of works that report on tools for measuring the learning that occurred during a system dynamics intervention (Vennix et al. 1993, Andersen et al. 1997, Cavalieri and Sterman 1997, Vennix 1996, Christensen et al. 2000, Vennix and

Rouwette 2000). These authors also point out that such an assessment is difficult to design, yet necessary if one is to reach conclusions about the final impact of the intervention. We fully agree with the necessity of measuring the learning that occurred during the system dynamics intervention. The lack of such a tool is a major deficiency in the HOLICS workshop prototype.

4 Generalization of the HOLICS Learning Framework

We believe these ideas from the design of the HOLICS workshop - the use of learning goals, learning theories, and instructional design principles - can be generalized to other system dynamics practice. Generalizing the learning goals of our HOLICS workshop we have:

1. Develop a structural and shared understanding of a dynamically complex system.
2. Develop effective policies to obtain the desired behavior from this system.

We believe these learning goals are applicable to any system dynamics intervention. They are consistent with the goals specified both for system dynamics practice in general (see e.g. Richardson and Pugh 1981) and for group-based system dynamics practice (see e.g. Wolstenholme 1990, Vennix 1996, Campbell 2001).

As demonstrated in section 4 of this paper, our framework of learning theories was applied to the HOLICS workshop design to support the learners in achieving the learning goals. As this framework is independent of content, we see every reason to apply it to system dynamics practice in general. To date, bits and pieces of the framework have been used, in an ad hoc way. Recognizing the fact that in complex systems knowledge is fragmented and dispersed among many individuals (Gonzalez and Sawicka 2000), it has been the common practice of system dynamicists to use intervention processes that encourage or require the active participation of diverse individuals in a problem-based, group process, during which the individuals were to improve their understanding of a complex system, i.e. reconstruct their mental models (e.g. Vennix 1996, Davidsen et al. 1999, Campbell 2000).

This practice is an application of the mental model and constructivist theories (learners must reconstruct their mental models to learn) and the situated learning theory (learning must be based on relevant and typical real-life situations). To correctly apply these learning theories it is necessary to implement the related instructional design theories: the elaboration and collaborative theories of instruction, and the anchored instruction theory. Choosing the correct type of instruction method to be used during a system dynamics intervention is one of the crucial, yet often neglected, factors influencing the successful achievement of learning goals:

> "Much has been written about the uses of systems dynamics to support learning in and about complex systems (see, for example, Sterman, 1994). Unfortunately, there is insufficient evidence to establish that or how system dynamics has contributed in significant ways to improved understanding. Moreover, what has been shown to be effective with system dynamics students and practitioners has not been established to be generally effective outside the system dynamics community. What is lacking is an instructional design methodology to support the design of system dynamics-based learning environments." (Davidsen et al. 1999, p.1)

Other specific learning and instructional design theories and principles implemented in the HOLICS workshop, such as the learning styles and preferences theory, the graduated complexity and multiple modes of instruction principles, appear not to have been used as frequently in SD practice.

What is significant about this generalized opportunity is 1) there are established learning theories consistent with our philosophy and methods, and 2) there are (and will continue to be developed) specific methods from the learning theory and instructional design communities about how to implement these theories for improved learning. As a community we have very few defined and consistently used processes or practices for successful system dynamics interventions, interventions where we have achieved a measurable improvement in people's mental models and behavior, and as a result in system performance. Yet there is a desire and a need to identify and apply good methods to system dynamics practice to improve our results.

In their analysis of system dynamics group model-building practice and methods, Andersen and Richardson (1997) point to some available process scripts. These scripts address individual steps - small segments of the overall group process. Andersen et al. (1997) identify the need for a more rigorous and defined system dynamics group model-building practice and call for a sound evaluation of the effectiveness of different scripts. Once the scripts yielding the best results are identified and defined, they believe it will be relatively easy and reliable to design an effective and efficient group model-building intervention. They state the identification of such scripts should be guided by both theoretical and empirical research. We believe this is relevant not only to group model-building practice, but to all types of system dynamics practice. In our opinion the research for improved system dynamics methods, techniques and procedures will be greatly augmented by formal learning and instructional design theories. Our HOLICS workshop is one example of how relevant theories can be implemented rigorously in system dynamics practice.

5 Conclusion

Our framework is a good starting point for developing a learning framework that can be applied to all system dynamics practice. To improve upon the framework there is an opportunity, or more forcefully a need, for members of the system dynamics community to do more research into the learning domain, and to collaborate with experts in that community to improve our understanding of learning theory and learning methods. In doing so we can significantly improve the effectiveness of our system dynamics practice, since even interventions that focus on problem resolution or alternative strategy selection as an outcome require consensus and hence learning to achieve that outcome (Winch 1993).

To conclude, we identify four *specific* suggestions for improving the learning that occurs in system dynamics practice:

1. For each system dynamics intervention, **define specific learning goals** that facilitate achieving the project goals. Specific definitions make it easier to assess whether or not the learning goals were met. Additionally, they allow for the evaluation of the learning goals in a broader context by using for example Bloom's educational objective taxonomy (Bloom 1956, Krathwohl et al. 1964).

2. We should **pay attention to individual differences** in learning styles in any type of system dynamics practice. By addressing the diverse learning preferences of individuals taking part in the process, we not only better facilitate learning of those individuals and the whole group, leading to consensus and commitment, but we more effectively prevent such undesired group process phenomena as groupthink.
3. We should **develop a more consistent and explicit approach to facilitating reconstruction of mental models** by implementing learning and instructional design theories. There has long been a question in our community about whether the time a system dynamics intervention takes can be reduced, or even should be (Sterman 2000, p. 899). We believe this is completely dependent on the time required for mental model reconstruction. If we know what activities are required and in general the amount of time needed for them, then we can 1) be most effective with the team, and 2) evaluate and communicate the tradeoffs more adequately if the team wants to take less time (a typical scenario these days).
4. We need to **design evaluation tools and methods** to determine if learning has occurred and been retained over time. It is crucial that assessment of learning does not focus on whether subjects *can* perform certain tasks in a virtual environment, but whether they *do* perform those same tasks in the real system. Only learning which leads to a change of participant behavior in the real system can be considered successful and consistent with the learning goals. For example, assessing interactive learning environment-based performance merely evaluates the learner's knowledge of this particular interactive learning environment. Such results are not conclusive and may not bring any insight into whether or not learning goals were met. What is valuable to assess is: Has the system dynamics intervention had a long-term impact on the mental models of the participants and on their behavior? Has this change in behavior had a long-term effect on the performance of the system?

Improved learning leads to improved mental models. These in turn lead to improved policies, which produce better system performance. Progress in all of the above areas throughout the system dynamics community will improve the learning that occurs in our system dynamics practice, and therefore improve our results and the results of those we are trying to help.

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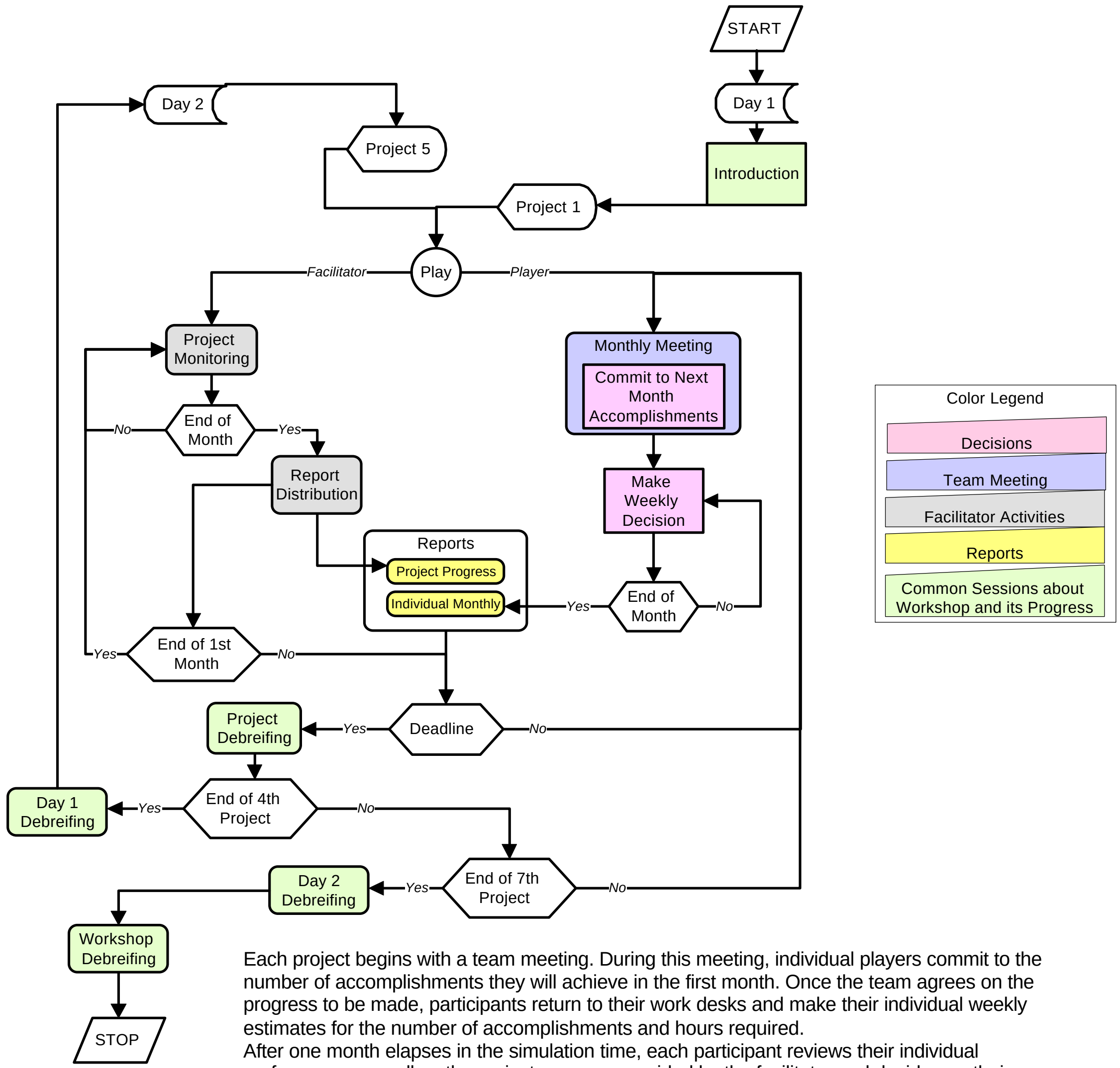
Appendix 1: *HOLICS Workshop Overview*



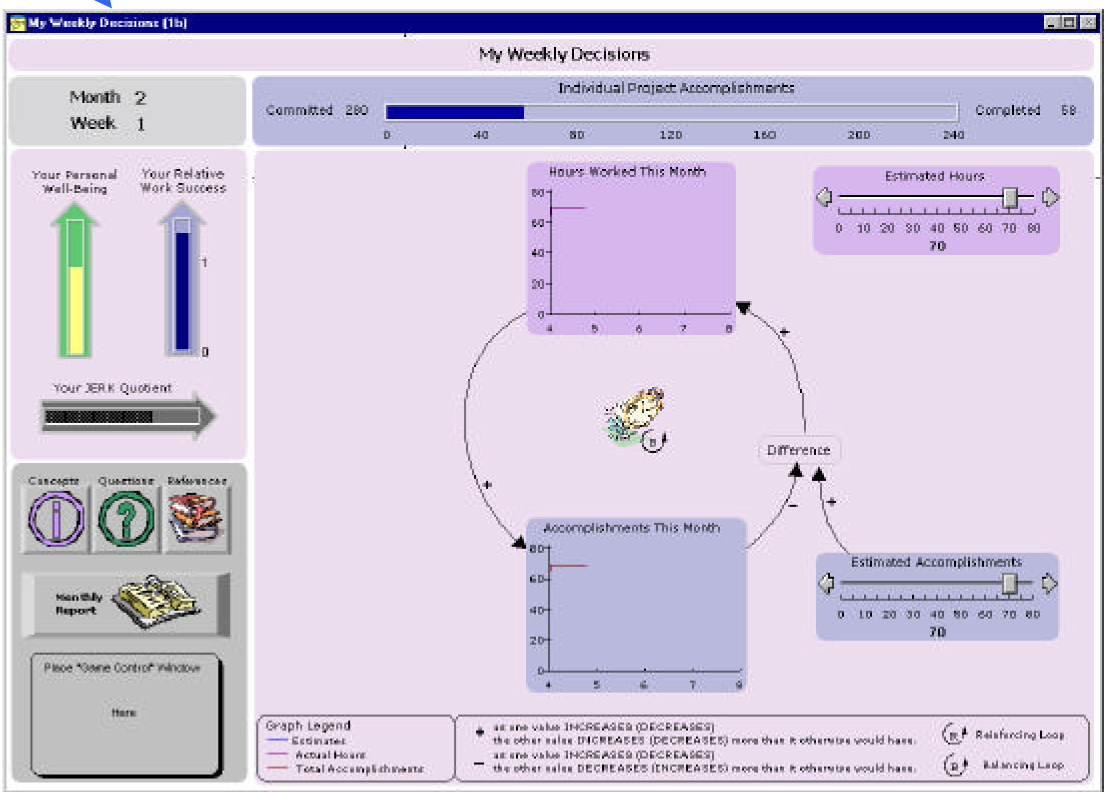
Each project begins with a team meeting. During this meeting, individual players commit to the number of accomplishments they will achieve in the first month. Once the team agrees on the progress to be made, participants return to their work desks and make their individual weekly estimates for the number of accomplishments and hours required.
After one month elapses in the simulation time, each participant reviews their individual performance as well as the project progress provided by the facilitator and decides on their commitments for the next month. These commitments are discussed during the next Monthly Team Meeting.

Figure I Flow diagram of the HOLICS workshop phases

Table I The *gradual* introduction of key concepts during the workshop

Day	*Project*	*Month*	*Screen*	*Concept*
I.	Introducing Project Management Concepts			
	1	1	*1*	➢ Introduction describing the Working Harder loop
		2	1	➢ *Previously Unidentified Tasks*
		3	2	➢ *Rework*
	Adding Personal Energy Level Concepts			
	2	1	*3*	➢ Quality
		2	*4*	➢ Personal Energy Level & Quality
		3	*5*	➢ Personal Energy Level & Hours Worked
	Explaining Concepts Related to Personal Expectations			
	3	4	*6*	➢ Personal Expectations
	4	1-6	*6*	➢ Furthering the understanding of all learned concepts and applying the knowledge gained.
II.	5-7	1-6	*6*	

PROJECT 1 (MONTHS 1-2)	PROJECT 2	PROJECT 3	PROJECT 4	PROJECT 5	PROJECT 6	PROJECT 7

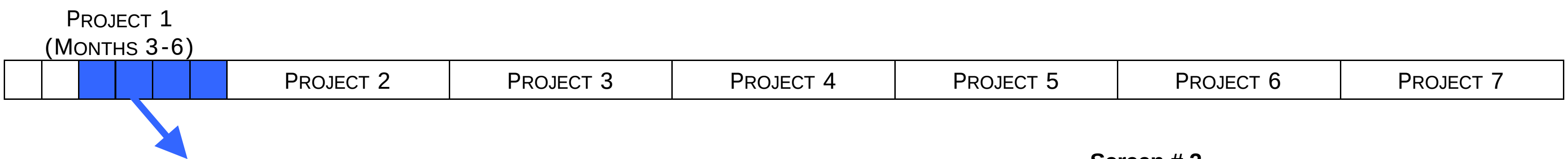


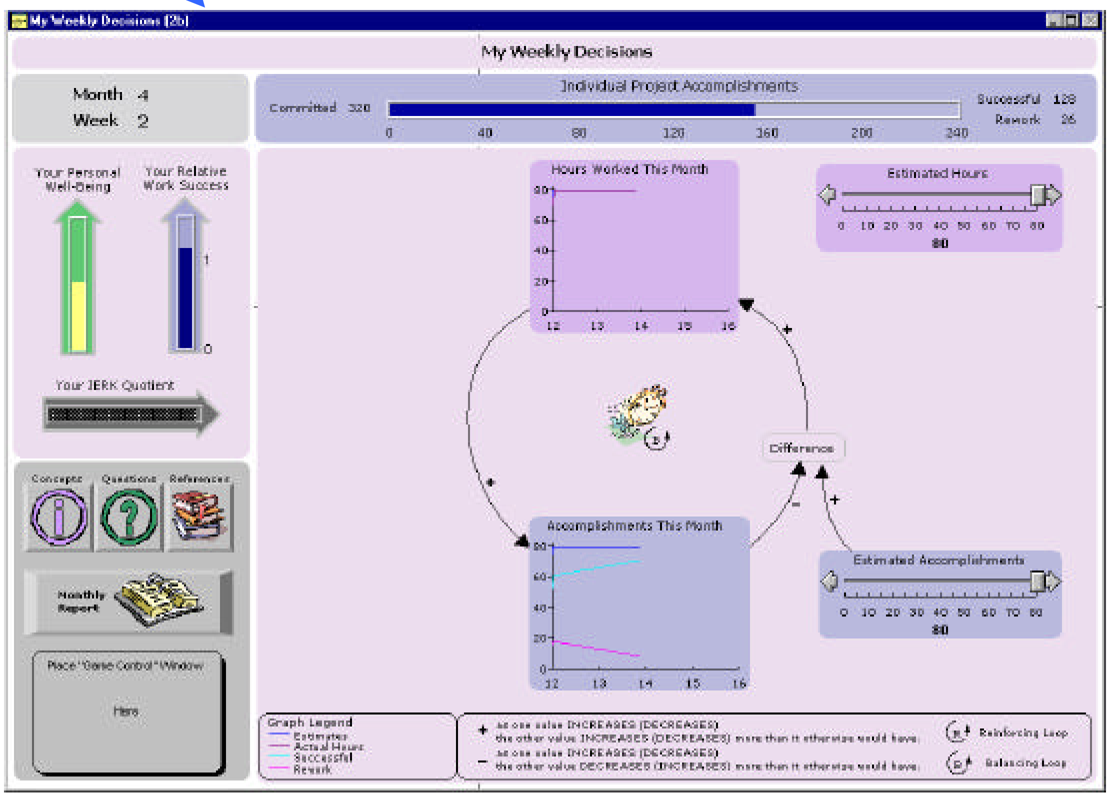
Screen # 1
Interface for: Project 1 (Months 1-2)

In adhering to the learning and instructional design theories that advocate the gradual introduction of new material, our workshop begins with a few key concepts and gradually incorporates more (see Table 1 Appendix 1). The interactive learning environment interface evolves with the workshop.

During the first project, only basic but important project management concepts are introduced. Screen 1 demonstrates the simple balancing relationship between estimated accomplishments, actual accomplishments, and actual hours worked. The difference between your estimated and actual accomplishments drives your actual hours worked.

Appendix 2: *Evolution of the Main HOLICS Interface Screens*





Screen # 2
Interface for: Project 1 (Months 3-6)

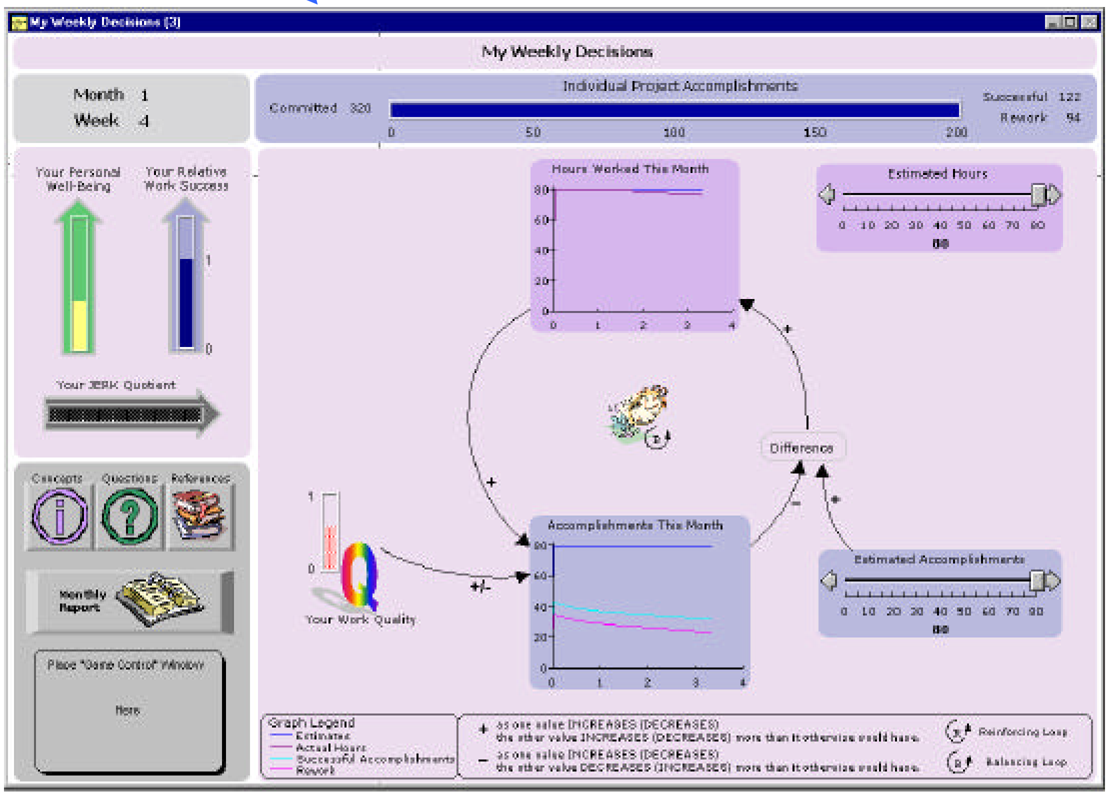
During the monthly meeting at the end of month 2, the team reviews the project status. They discover that while everyone has been easily completing their agreed upon accomplishments, the number of tasks required to complete the entire project has grown. This is due to the standard project phenomenon of previously unidentified tasks - tasks that could not have been predicted when the project was still in the early phases.

During month 3 the team discovers another standard project phenomenon: that not all the accomplishments they have completed have been completed successfully. Screen 2 provides the participants information on the amount of rework (tasks that must be redone) they are creating as they complete accomplishments. At this point, this rework amount is based on the project lifecycle - the closer to completion the less the rework created. The team is given the rest of the project time (months 4,5,6) to develop strategies to account for unidentified tasks and rework, and complete the project successfully.

Appendix 2: Evolution of the Main HOLICS Interface Screens

PROJECT 2
(MONTH 1)

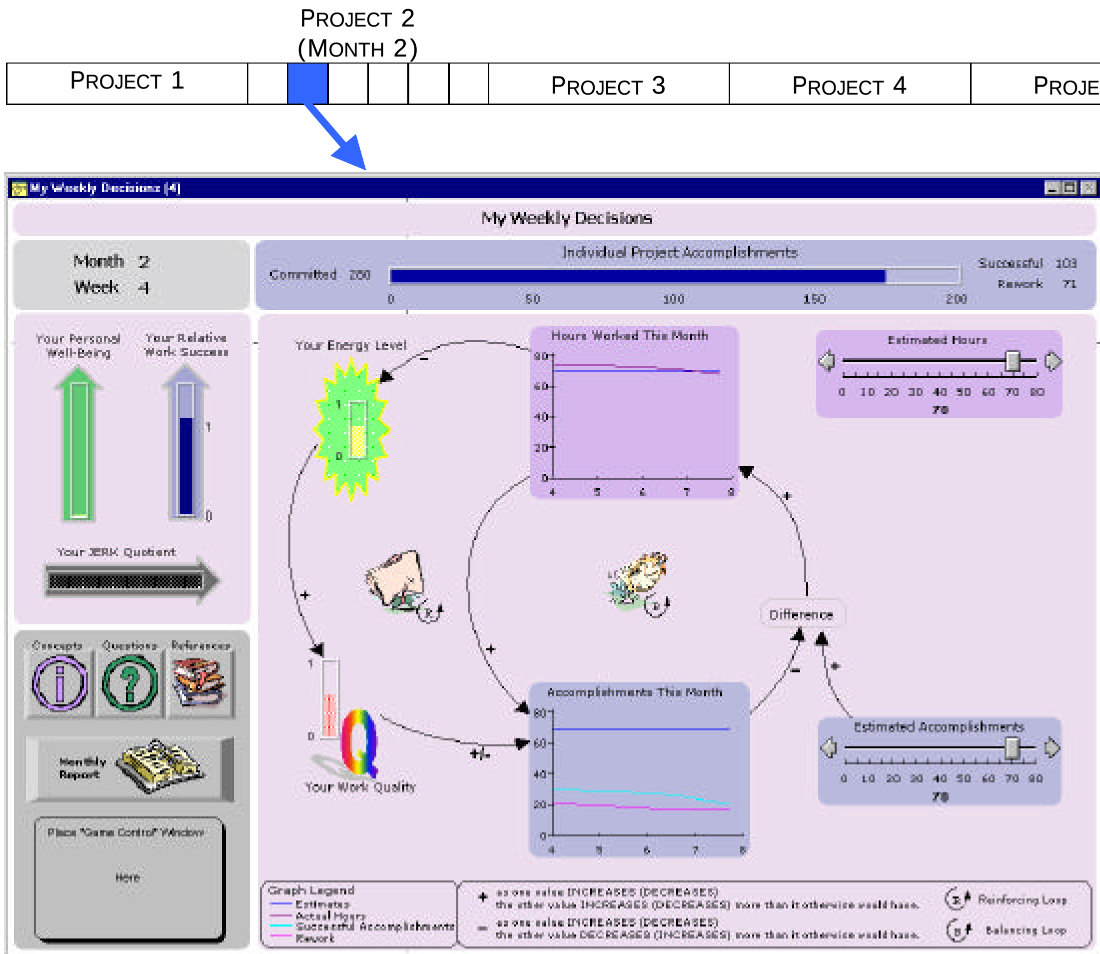
PROJECT 1							PROJECT 3	PROJECT 4	PROJECT 5	PROJECT 6	PROJECT 7



Screen # 3
Interface for: Project 2 (Month 1)

During project 2, the concepts of work quality and personal energy level are introduced. Screen 3 provides the participants information on how work quality impacts accomplishments: as your work quality declines you complete fewer total accomplishments in the same amount of hours, and the amount of rework you create increases.

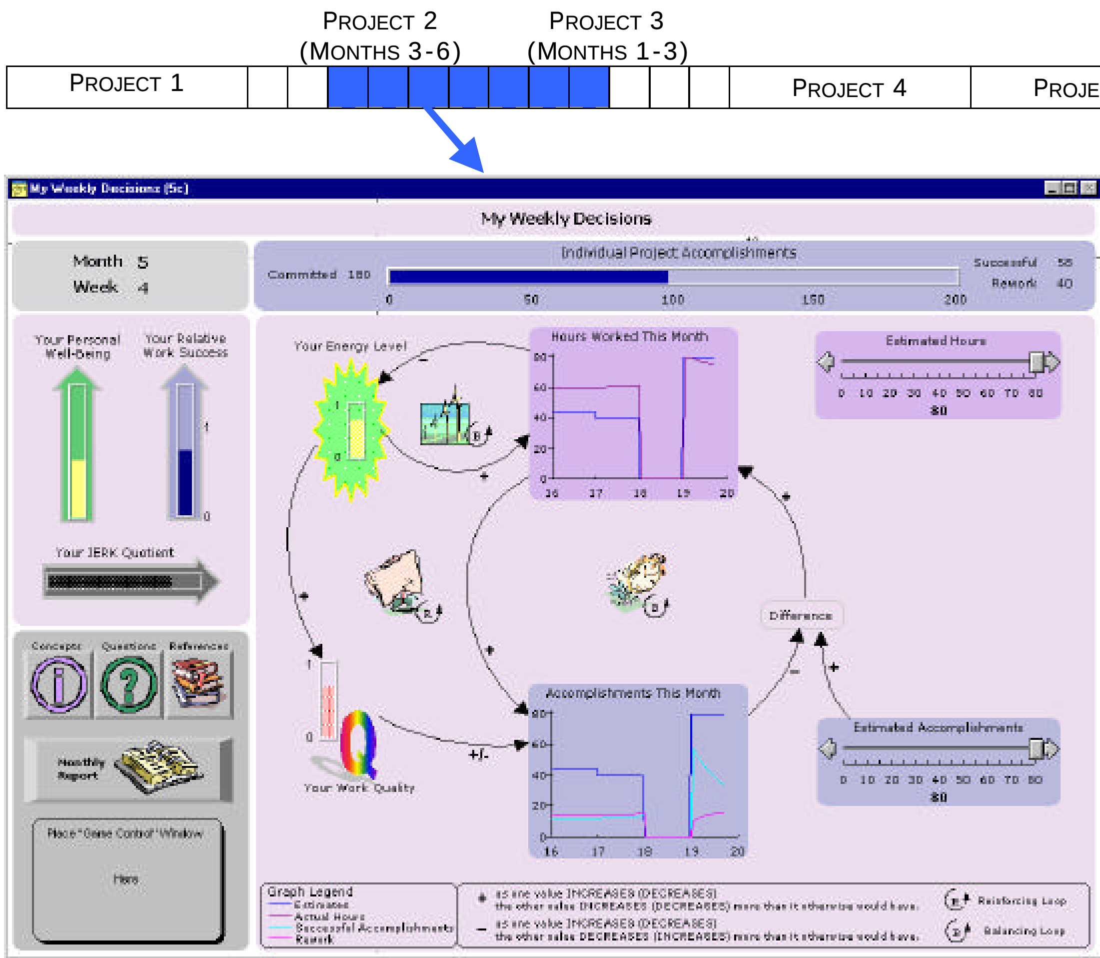
Note that because this individual has been continuously working 80-hour weeks, his or her jerk quotient has gone up - this means that spouse, family and friends alike are unhappy.



Screen # 4
Interface for: Project 2 (Month 2)

Screen 4 provides insight into the underlying cause of work quality variability - personal energy level, which is dependent on the number of hours worked. This reinforcing loop can become a vicious cycle with low energy level and poor quality reducing the number of successful accomplishments, and keeping the hours worked high.

Note how personal well-being has emptied - the individual themselves no longer feels good.

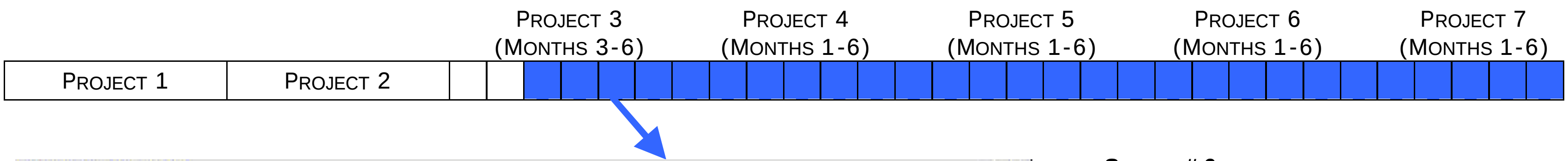


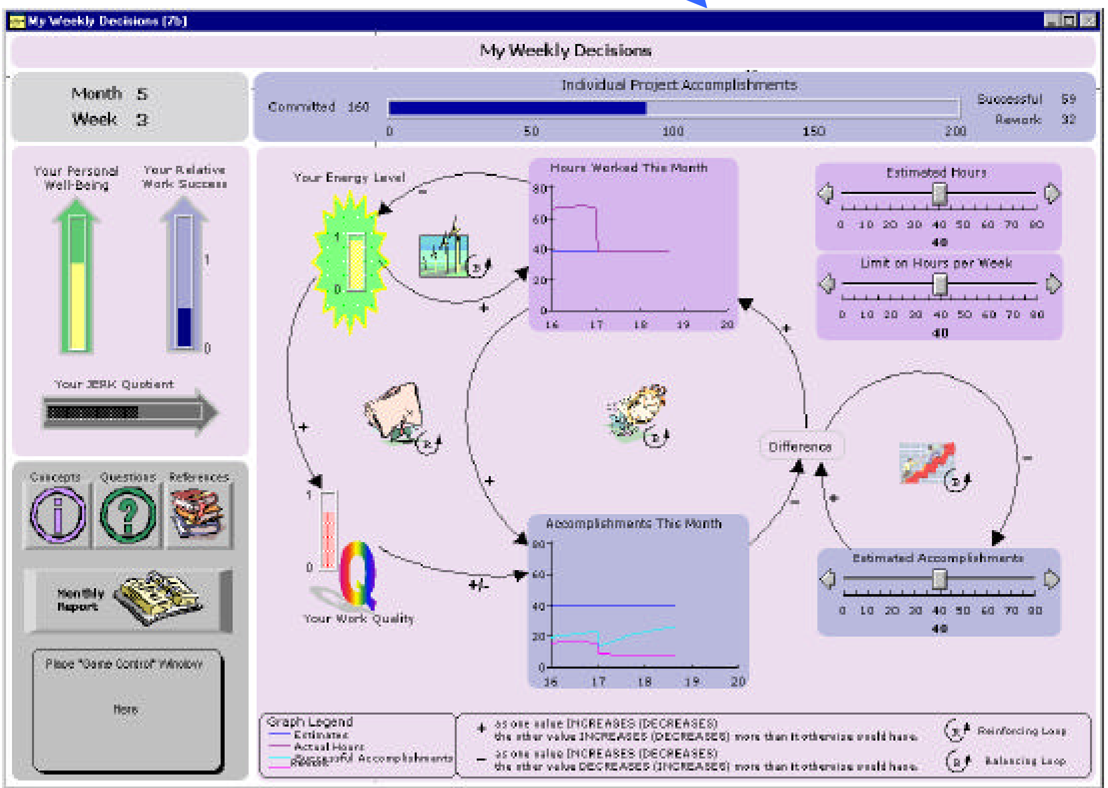
Screen # 5
Interface for: Project 2 (Months 3-6)
Project 3 (Months 1-3)

Screen 5 introduces a third feedback concept - the impact of personal energy level on hours worked. When your energy level drops below a critical point, you are physically unable to work the extra hours, even if you want to. This is known as 'worker burnout'.

Note that this individual chose to take a one-week vacation to increase his or her personal energy level. It had an immediate but only short-term effect. The *pattern* of long work hours creates the undesirable result. This result cannot be significantly changed by a one-time *event* such as a vacation.

Appendix 2: *Evolution of the Main HOLICS Interface Screens*



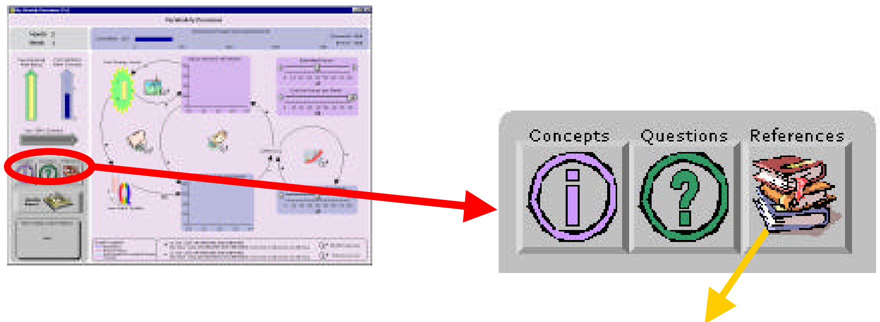


Screen # 6
Interface for: Project 3 (Months 3-6)
Project 4-7

During project 3, the concept of personal expectations and their contribution to worker burnout is introduced. An important personal energy management strategy lever is also introduced - placing a limit on your hours worked per week regardless of the number of accomplishments. The team is given the opportunity to use the follow-on projects to develop and test various strategies for successfully completing projects now that they understand the structure that underlies the dynamics of high and low productivity cycles.

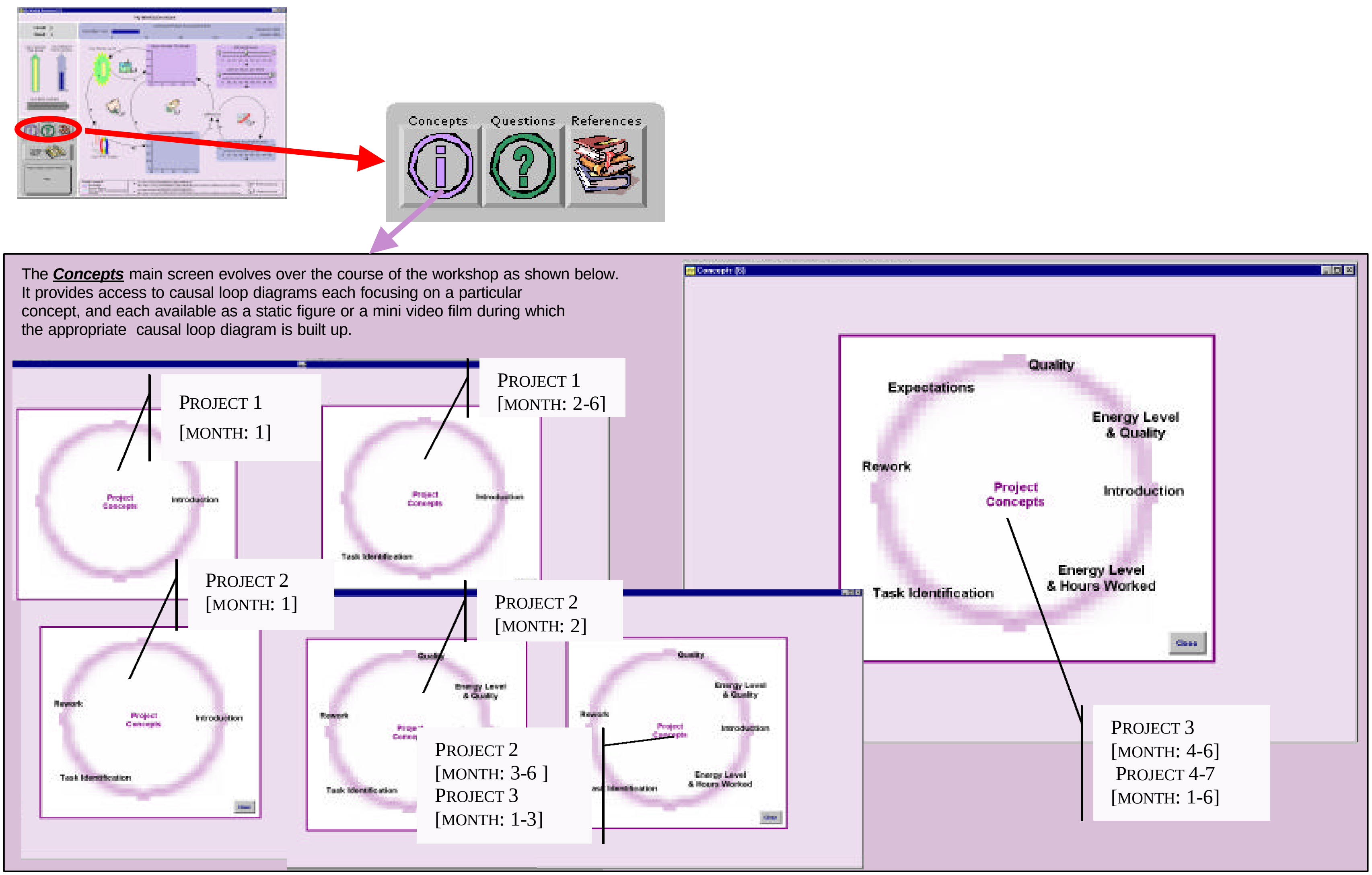
Note that in figure 5 of the main body of this paper, which shows the results of three different project completion strategies, the most successful one was a participant who chose to limit his or her hours worked from the beginning of the project (player 2). The others are exhibiting worker burnout.

__Appendix 3__: The Reference Section in the HOLICS Interface Screens



References section contains various references (such as articles, book references, web page links, quotes, etc.) relevant to the workshop theme.

__Appendix 3__: Evolution of the Concepts Section Screens in the HOLICS interface



Appendix 3*: Evolution of the Questions Section Screens in the HOLICS Interface*