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ENHANCING THE PRODUCT DEVELOPMENT PROCESS VIA DESIGN PROGRESS AND KNOWLEDGE ASSETS MANAGEMENT WITH VISUAL DESIGN EVALUATIONS

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ABSTRACT
With the advance of IT infrastructure and computer-based engineering solutions in manufacturing enterprises, design engineers have at their disposal numerous computer-based tools and methods that facilitate product development activities. Although these tools and methods have improved the quality and speed of product development processes, there remain many inefficiencies due to ineffective use and/or sharing of design knowledge and errors in communication. This paper identifies the typical issues in communications and design knowledge sharing in collaborative design environments and introduces a computer-based solution to enhance the product development process in terms of collaboration and design knowledge sharing. The solution is focused on preventing communication errors and the timely use of design knowledge assets, including design documents, specifications, test results, reports, reviews, memos, meeting minutes, and the like.

Keywords: Design collaboration, product development process innovation, design knowledge sharing.

1 INTRODUCTION
This paper describes a current study of the product development process. The goal is to identify opportunities to enhance the process by assisting design engineers to effectively manage their design knowledge assets and facilitate the team communication relevant to evaluations and decisions on alternative designs. To realize the identified opportunities, a new software tool was introduced to enhance the product development process and facilitate the capture of project assets, decisions, and communication.
Section 2 presents a linear, phased description of the product development process. Overlaid on the phases are branches of digital assets that correspond to design alternatives, as well as levels of activity and communication at the individual, team, and organizational levels. Section 3 describes life cycle issues within the product development process as they relate to specific types of assets. Section 4 describes communication issues related to the number and type of participants whilst progressing design evaluations. Section 5 illustrates the use of a revision management system as the foundation for tracking a project's assets and the exploration of design alternatives. Section 6 contains a case study based on Air Conditioner design at a large consumer products manufacturer.

2 PRODUCT DESIGN AND DEVELOPMENT PROCESS
Every product design and development project has phases. While the general process can be described as shown in the figure 1, the detailed activities and tasks may vary depend on the types of products. Products can be categorized generally as innovative, market-driven, platform and customized [1].

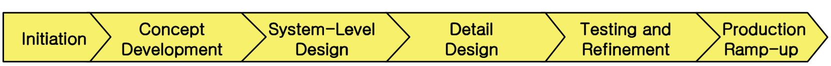

Figure 1. Typical Product Design and Development Process

During the product design and development process many organizational and/or functional stakeholders such as the management, marketing, sales, R&D, manufacturing, suppliers, customers, 3rd party contractors and the like must communicate and interact. Since each stakeholder has preferences and/or requirements on the expected values, functions and performances of the product, extensive communications and decision making amongst the stakeholders are essential for a project to be successful. To integrate the decision-making process among heterogeneous and distributed stakeholders, the use of information technologies and networking capabilities has become a critical capability [2].

2.1 Work Environment for Product Design and Development

Activities in the product design and development process are conducted at various levels of detail, by a variety of constituents with various levels of expertise. The required and actual levels of detail depend on a variety of conditions including the project phase and decision points within the development process. For example, the levels of work environment can be categorized as shown in Table 1.

Table 1. Category of Work Environment

Level Category	Key Characteristics
Company	1. Top management decision making needed 2. Reporting major milestones 3. Communication with customers, partners, suppliers, etc. 4. Company-wide IT systems are provided with the focus of high-level management.
Division/Team/Group	5. Groups with different expertise and background often communicate to make decisions with different perspectives and terminologies. 6. Tradeoff-analysis is needed for competing objectives represented by different groups. 7. Extensive but often ineffective communications occur in both formal and informal fashion.
Individual	8. The preference on work process and environment varies depending on the individual expertise and work style. 9. Intermediate deliverables are often managed in ad hoc fashion.

As the characteristics of interactions and communications at each level of the work environment are different, the available or preferred information systems and computer-based tools may vary as shown in Figure 2.

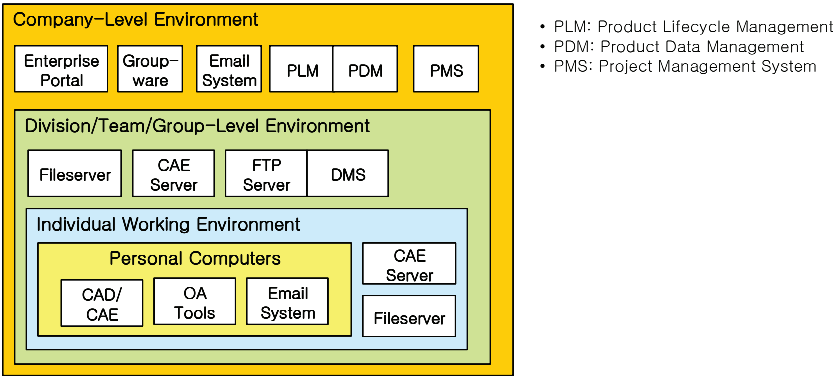

Figure2. Information Systems and Computer-Based Tools at the Work Environment

2.2 Design Alternatives

During the life of a project, many design alternatives may be proposed, analyzed, and compared to one another. Based on individual and/or group decision criteria decisions are made for a certain design to pursue further. Each alternative typically results in branches of development and the generation of assets for design, analysis, and evaluation. Some of the branches are deemed infeasible and die. Others produce useful concepts that are incorporated into other branches. Figure 3 illustrates the project phases augmented with branches of concept development.

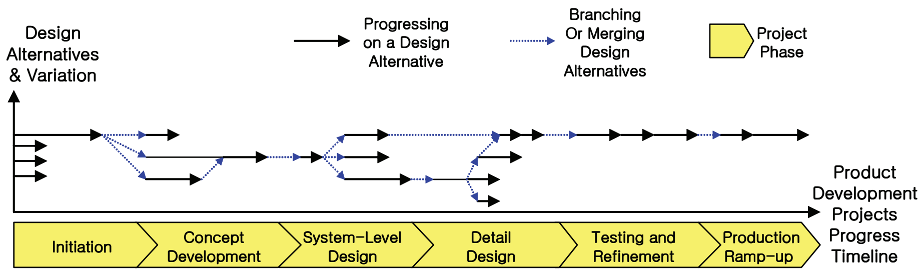

Figure 3. Life Cycle of Design Alternatives and Variations

Design alternatives often need to be considered in parallel, branched into several sub alternatives, and merged into one or more design alternatives. The design alternatives and associated design decisions can also be hierarchical as depicted in Figure 4. In other words, more design alternatives at the individual level may need to be considered for a design alternative at the upper level of work environment.

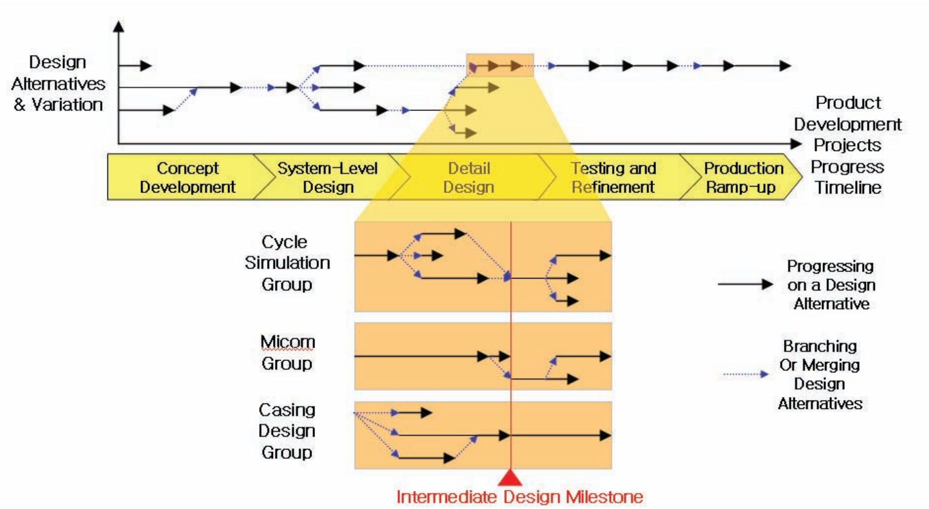

Figure 4. Hierarchical Design Alternatives and Variations

The significance of each design alternative and associated analysis and decisions may change over time. It is important to capture, manage, share and reuse this design knowledge as well as to manage the history and progress of design alternatives. A single participant might work on a single branch, or multiple participants may share a single branch.

Also, while each design engineer or stakeholder works within his/her work environment with activities and tasks progressing in parallel, there must be intermediate or formal milestones where the evaluations and decisions made locally need to aggregated and projected to the higher level of work environment so that all the stakeholders share the information and knowledge as well as monitor the status and progress of a project.

2.3 Communications and Knowledge Sharing

In a product design and development project along the lifecycle of design alternatives, the intensity and frequency of communication for giving opinions, negotiating on options, sharing information and knowledge, and the like will vary across the range of work environment as shown in Figure 5. The communication often needs to be based upon common measures such as financial interpretation (i.e., cost) and performances (e.g., power consumption, structural stability, manufacturability, etc.) As more stakeholders participate in the communication channel it is often difficult to find appropriate measures because each stakeholder has different expertise and background, and thus possibly interpret the measures and its relative significance differently.

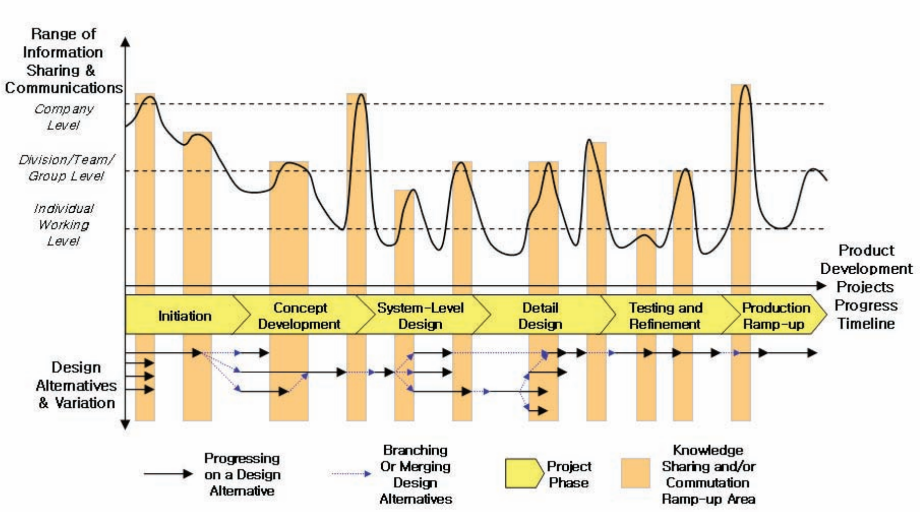

Figure 5. Varying Intensity of Information Sharing/Exchange and Communication throughout the Product Design and Development Process

Top-down knowledge management systems often fail to provide day-to-day value. Corporate information systems typically attempt to facilitate the information and knowledge exchange/sharing amongst stakeholders, not only within but also outside a company. However, such top-down, directed systems often focus on the major milestones of a project at the expense of day-to-day indicators that actually enable accomplishment of those very milestones. Although a system like PLM manages the versions of CAD files and engineering documents, it is more often used for managing deliverables of formal design reviews, official releases of a confirmed design, and so forth. A system like the PMS (Project Management System) also tries to enforce the management of official or prescribed deliverables, issues, cost analysis, and so forth in order to track the progress and sense potential risks. Embedded in such a PMS, project management methods like Stage-Gate Process, PMBOK based project management, and Earned Value Management are used to ensure the project goals to be accomplished with planned budget and time [3].

However, these systems and methods are often disconnected from individuals' work environment. Although many information systems and computer-based tools are accessible from individual PCs, project plans, requirements, design tasks and resulting outputs are often inaccessible. For example, analysis results from CAE simulation are stored locally or in a fileserver and the engineer reports the result to others via separate documents or emails. While a designer works on parts and assemblies using a CAD tool, he/she may summaries the design candidates and their comparisons in a document and sends it to colleagues for review. Upon a group design review a certain design alternative is selected for the further progress, and relevant reports and files may be submitted in a project management system for deliverables of a milestone. This implies that the personal design tasks where many informal notes, documents, engineering memos on test results are created may not be transparent to colleagues nor team managers.

Communication paths are also often broken. In some cases, it is not clear who is responsible. In other cases, there is simply no communication channel for one team member to report an issue to another team member. In other cases, there is no mechanism for recording the communication so that the issues can be tracked and prioritized.
If a system could assist designers to manage personal work environment and formal/informal work deliverables and yet project the individual evaluations and decisions seamlessly to the upper-level of communication, it could potentially create a collaborative work and communication environment where each individual working progress as well as knowledge can be shared and monitored effectively. Furthermore, such a system could possibly help product development teams to identify and analysis the value of individual and/or team's knowledge assets so that they can better manage and enhance their design knowledge to become knowledge enterprises [4].

3 PROGRESS IN PRODUCT DESIGN AND DEVELOPMENT PROCESS

Although the progress of a project is often abstracted to phases, at each stage there exist many paths of activity, branches of development, and interactions amongst participants. Although many projects share similarities, each is unique. Even when the product is evolutionary rather than revolutionary, it is often difficult to predict the lifespan of design alternatives and the life cycle of communication and deliverables generated during the development process.

3.1 Product Development Progress

The progress of a generic product design and development can be viewed to have a lifecycle, in which design concepts are initially conceived, modified, branched into several options to be explored in parallel, merged into a consolidated option, and released to stakeholders to review as described in Table 2. In each step of this lifecycle decision making activities and tasks are conducted and the relevant design knowledge assets will be utilized or generated.

Table 2. Progress Types in a Generic Product Design and Development Project

Category	Key Characteristics
Initiation	1. Initial design alternative(s) is defined. 2. Key evaluation measures are determined and defined.
Revision	1. Certain design factors, attributes, decisions are changed in order to improve the aggregated design evaluation measures. 2. Nevertheless, the overall concept of the design remains unchanged.
Branching	1. New design concepts are identified. 2. Further analysis and validation of the concepts are decided. 3. Tasks are planned so that separate exploration of the design concepts proceed.
Consolidation	1. Design concepts are merged into another concept so that an integrated design concept is further developed with focused efforts.
Release	1. Design(s) has reached at a certain level and needs to be shared with other team members, groups, stakeholders, etc. 2. Design(s) could be released for the purposed of an informal checkpoint as well as a formal milestone of a project.

Although systems like PLM, PMS, etc. could capture formal deliverables at each milestone, it is not trivial to enforce other stakeholders as well as design engineers to manage all the inputs/output and relevant design knowledge assets contributed to decisions made and relevant histories along this lifecycle of progress. Those systems often provide features to manage the history of files and documents, it requires design engineers to purposely submit or register those files and documents into those systems. In many ordinary product design and development organizations these extra steps or efforts become cumbersome for design engineers and therefore only officially enforced deliverables are submitted and managed.

3.2 Design Knowledge Assets

Product design and development involves knowledge-intensive activities, tasks, and communications. As the market becomes more demand or consumer driven, the use of information technologies, computer-based tools and methods, and networking capabilities is essential to expedite the progress and obtain the desired results on time. Common knowledge assets include the following:

1. Product requirement and specifications
2. CAD files
3. CAE analysis results
4. Analysis results in spreadsheets
5. Reports, memos, and other engineering documents
6. General notes and documents
7. Emails

3.3 Carrots and Sticks

The ideal system provides value to its users at every level. For example, a project manager needs accurate estimates and actuals on which to base a project plan. These data are typically collected by requesting estimates and periodic status reports from team members. However, estimates are often inaccurate and status often changes, so the overhead of collecting and maintaining accurate estimates and status frequently becomes a burden. The manager does not have enough information to ensure accuracy, and the team members do not have enough time to update the information.

Contrast this with a project in which estimates are drawn from historical performance, and status is drawn directly from the status of deliverables in the repository. As work progresses, both managers and participants can see the status on any component of the project. Meetings can focus on "what needs to be done?" rather than "Where are we?" Estimates can be based on the actual time to complete deliverables. This is straightforward for evolutionary work, and a growing organizational knowledge, backed up by data in the repository, makes it easier to forecast on revolutionary components of a project that have no direct historical precedent. Estimates are based upon fact rather than perception.

The first step to realizing such a system is to get team members to commit their work to a repository. The repository should contain all of the project assets, not just summaries at milestones. There are many incentives for individual participants:

- keep track of changes
- go back in time to a previous configuration
- maintain multiple designs/concepts/releases
- track multiple projects
- understand/communicate changes
- resolve conflicts
- re-use with confidence

There are also incentives for project managers and system engineers:

- gather actuals and deliverables for planning/scheduling
- see where activity is and is not happening
- understand sources of conflict
- expose bottlenecks sooner rather than later
- facilitate audits
- determine and analyze root causes
- track data transfers to/from vendors and customers

As a project evolves, the repository will be similar to a sketch followed by a detailed ink. Requirements, performance objectives, and tasks are first entered and provide the sketch that outlines the vision for the project. As the project progresses, assets are added, branches are made, alternatives are explored, reinforcing parts of the sketch and erasing others. Tags and milestones, made explicit in the repository, are the ink that realizes the project goals.

4. DESIGN EVALUATIONS AND COMMUNICATION

4.1 Communications in design engineering

As the number of stakeholders and participants involved in a project increases, the effective communication becomes a challenging tasks as well as the prerequisite of a successful project. Communication during product development can be grouped into the following categories (any reference?).

1. Identifying needs and defining requirements
2. Recognizing what others have done and understanding the effects of those accomplishments
3. Determining whether actual performance meets expectations
4. Deciding which alternatives to pursue
5. Discussing outstanding issues
6. Reviewing status and monitoring progress

4.2 Evaluation of designs for decision making

Product design and development involves a series of decision-making processes: identification of options or choices, development of expectations on the outcomes of each choices, and formulation of a system of values for ordinally ranking the outcomes and thereby obtaining the preferred choices [5]. To facilitate these decision-making processes in multi-disciplinary design projects with multiple stakeholders in various viewpoints and communication levels, a probabilistic interpretation of design's acceptance is well suited [6]. In the probabilistic evaluation scheme, decision making in design is based on the following three factors.

1. Expectation (Specification, Preferences)
2. Performance measures and relevant design decisions (functions, features, etc.)
3. Expected Acceptance or satisfaction level.

Assuming that the major portion of communications during product design and development projects are aimed to facilitate the decision making activities and tasks the categories in communication discussed in Section 4.1 can be associated with the three factors of decision making.
Both the visibility of performance indicators and the frequency with which they are updated are crucial to the success of a project. Indicators must be visible to those who can influence them, are being evaluated by them, and are evaluating them. They should be updated as close to real-time as possible. Weekly or monthly meetings might catch problems, but daily, hourly, or change-based updates to indicators can expose problems before they have a chance to become project-threatening. Requirements inevitably change over the life of a project, so the system for recording, quantifying, and displaying the metrics must be flexible. Finally, the metrics must measure things that matter.

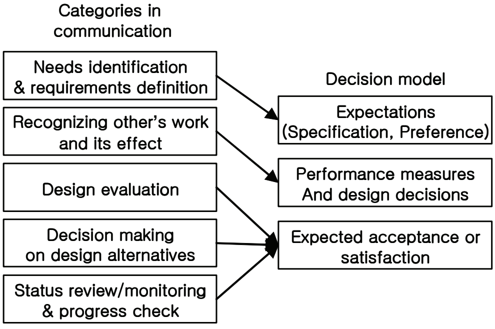

Figure 6. Association between Communication Categories and the Decision Model

This implies that the capturing and managing the decision model factors within the individual work environment and seamlessly projecting them onto the group and company level work environment could facilitate the communication in a project to a great extent. Thus, product design and development process can be greatly enhanced if a tool can provide an effective way to visualize and manage these decision model factors as well as keep track of the history of designs and decisions made while design engineers and stakeholders work on each one's given tasks.

5. REVISION MANAGEMENT AS THE FOUNDATION

Most projects use a variety of tools to facility communication, process and capture. For example, a simple project might use telephone and email for communication, a wiki for collaborative document editing, and a shared file system in which to store assets. Each of these tools serves a specific purpose, and each has a significantly different user interface and experience. However, the tools are disconnected, and without end-user discipline, project knowledge often ends up being difficult to find, complicated to re-use, and increasingly fragmented.

This study made extensive use of a Subversion repository as the primary storage mechanism for project assets. The intent was to keep all project assets in the repository, then provide various context-appropriate interfaces to view and modify the repository contents.

5.1 History Matters

Why not use a database or shared file system? History is the key benefit of using a repository rather than a shared file system. A repository provides not only a hierarchy for where to locate an asset, but also a history for identifying when an asset was in a specific state. This combination of both where and when is incredibly powerful when applied to every project asset.

5.2 Single Point of Entry

Even if project data are located in different databases, file formats, or physical locations, providing a single entry point makes the data accessible to participants. In many cases project data are kept directly in the repository, even if their 'native' environment has its own notions of version control. In other cases, the repository contains versioned links to various states of project data in other locations.

5.3 Centralized vs Distributed

There are two major types of repositories: centralized and distributed. In the centralized model, each participant may work in a sandbox, but a connection to the repository is required for committing changes or getting changes from other participants. In the distributed model, each participant keeps a complete clone of the repository, thus enabling 'offline' commits and other operations. Merging happens when the participant connects with other participants or with the 'reference' repository. This study used a centralized model.

5.4 Per-File vs Aggregate Versioning

Some revision management systems track changes to file contents. Others systems track changes to not only the contents of files but also directories. Most product development efforts involve a variety of files and file types, and the history of what files were created/destroyed and how they are related is just as important as the history of what the files contain.

5.5 Ease-of-Access.

Experience has shown that the system must be accessible from a variety of contexts. A PDM system from a CAD vendor is inappropriate for housing a design document when it requires the owner of the design document to install/start the CAD software just to update the document. A web-based front-end to the PDM system might make the contents of the PDM system easier to view and eliminate the need for installing PDM client software. However, a web-based interface cannot address every need of every constituent. An open, extensible, stable interface makes the system easy to customize for different types of users and different types of workflow.

5.6 Subversion

Subversion was designed with these characteristics in mind [7]. It supports WebDAV, so it can be integrated directly with the file system user interface on todays operating systems. It defines the basic revision management operations (import, checkout, commit, branch, merge, compare) and supports any file type and reasonable file sizes. It works with any file type. It tracks changes to directories as

well as individual files. It works seamlessly with a variety of authentication protocols and mechanisms.
Oculus' Revision Manager software provides a graphic user interface to Subversion repositories. The graphic display of branches and changes correlates directly to the product development structure described in Section 2 [8].

6. A CASE STUDY

In order to verity the effectiveness of using a computer-based tool to manage the product development progress and design knowledge assets as well as facilitate the communication amongst stakeholders, a field pilot study on an actual product development project is on-going. This section describes a simplification of this pilot study to illustrate the concept on how the Revision Manager can be used in a product design project.

6.1 Product design project

Air conditioners are a typical electronics product which requires expertise from multiple disciplines to design. Various backgrounds and experiences are required, including thermodynamic cycle analysis, structural analysis, fluid mechanics, and systems controls with microprocessor programming skills. In some cases the design involves an entire HVAC system, thus requiring even more disciplines such as architectural design, and building energy consumption modeling. The example case of this paper is a commercial air conditioner as shown in Figure 7. To be more specific, it is for an outdoor unit of a commercial air conditioner.

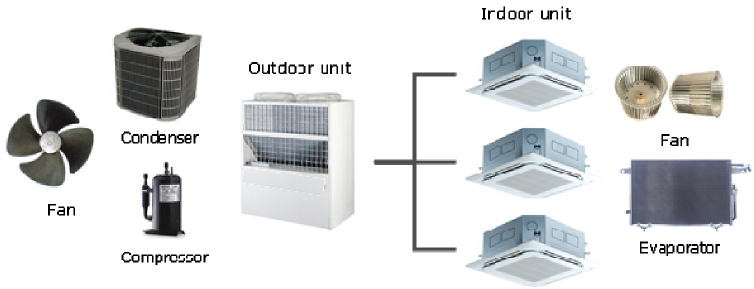

Figure 7. Product Structure of a Commercial Air Conditioner

As shown in Figure 7, the core components of an air conditioner are compressors, heat exchangers (evaporators and condensers), and capillaries, which constitute a thermodynamic cycle that determines the heating and cooling performances. Other important components are fans and motors, and casings that contribute to the noise and vibration as well as the air flux within the system.

6.2 Design criteria

The major design criteria and key performance metrics are categorized as shown in Table 3. In the initial phase of the project, goal or requirement setting activities are conducted for these key metrics. Design engineers participating in the project are grouped into teams, each of which contributes design decisions that contribute a subset or all of these metrics.

Table 3. Design Criteria for a Commercial Air Conditioner

Criteria	Key Performance Metrics
Performance	1. Cooling and heating capacities 2. Energy consumption 3. Noise level 4. Vibration 5. Structural stability and strength 6. Controllability (Temperature control)
Ease of Installation and Maintenance	1. Weight of frequently serviced parts and their assembly characteristics

Environmental Sustainability	1. Percentage of recyclable materials 2. Refrigerant characteristics
Supply Chain Efficiency	1. Use of common versus customized parts 2. Part supplier network for major components

6.3 User needs for managing the design progress

In this example case the stakeholders are a project manager, the cycle team, the structure team, and the logic team as shown in Table 4. Each stakeholder has a different set of roles and responsibilities in the project.

Table 4. Stakeholder Definition

Stakeholder	Role and Responsibility
Project Manager	• Manages the overall progress of the project. • Guides overall design decisions to meet the design criteria.
Cycle Team	• Manages the cycle performance of the design. • With the parts and components design by the structure team analyze the cycle performances in various operating conditions.
Structure Team	• In charge of detail design of parts and selecting appropriate components. • Manages the design criteria such as noise and vibration.
Logic Team	• Develops the systems control logics with various operating scenarios and temperature settings.

To better manage the design progress the manager, team leaders, and team members want to be able to do the following.

1. Team members want to see how other team's work is progressing and know if any design changes and/or decisions are made.
2. The cycle team wants to make sure that the structure team has the correct test settings for the indoor units.
3. Design engineers want to keep the change history of his/her own work and see how the design performance metrics of his/her interest has changed.
4. The design manager wants to see not only the overall progress but also the key design performance metrics to understand how good the current design is.

6.4 Project model of the air conditioner project

6.4.1 Project model structure

As shown in Figure 8 Design project folder named "cambridge" is created in a repository of the Revision Manager so that all design engineers in teams and the manager can access the contents.

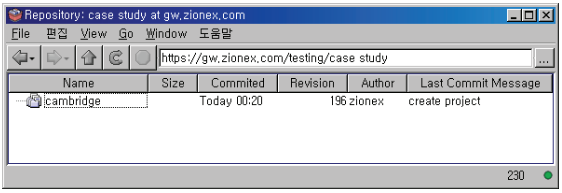

Figure 8. Design Project Folder in the Repository

Figure 9 shows the main window for viewing the project. As shown in the left hand side window the knowledge assets are divided into three folders representing three teams in the project. On the right hand side how each team is working on their part of the design and design changes are made. The *Trunk* indicates the integrated design from which all design teams are branched out. From these branches each team works on its own parts of the design project. It is also common that a certain team may consider an alternative design in parallel with the original design. For example, the structure team created another design to evaluate relevant options.

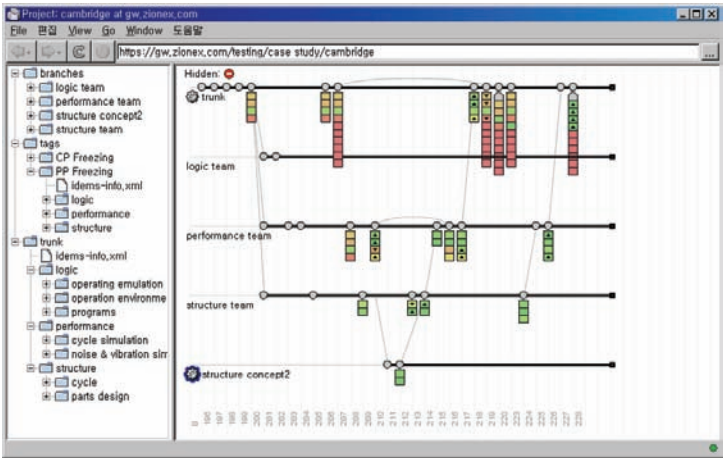

Figure 9. Project Window for Viewing the Project Progress and Contents

Figure 10 shows the performance metrics defined by the project manager. The first four metrics are the key design criteria of the outdoor air conditioner unit. The next six metric is for keeping track of the formal design milestones. For example, the CP stands for concept planning. By defining metrics in this fashion the manger can visually monitors how well the design criteria are satisfied and how the project is progressing in the formal project process.

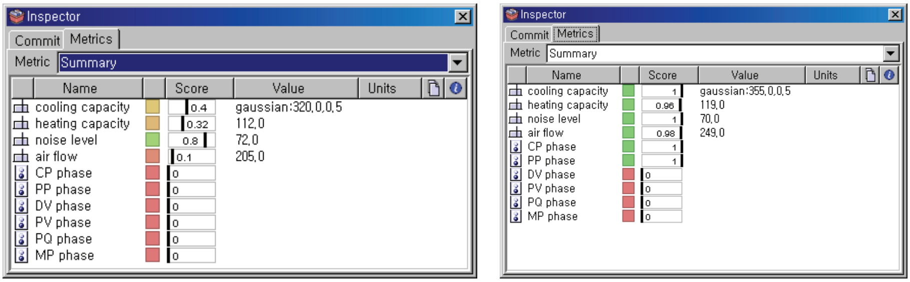

Figure 10. Design Key Performance Metrics

The key performance metrics can be modified by the design engineers or the manager via entering values. However, if possible, it is better to integrate these metrics with files and documents that design engineers actually work with. Figure 11 shows the design knowledge assets managed in the Revision Manager. While the left hand side window shows the assets managed in the repository, the right hand side window shows the locally managed assets that are checked out from the repository and always synchronized with the server. If a design engineer works on a certain sets of files and documents, the changes can be easily updated onto the server. If those files and documents are associated with performance metrics, the changes in metrics are also updated onto the repository and readily available for other team member and the manager to monitor.

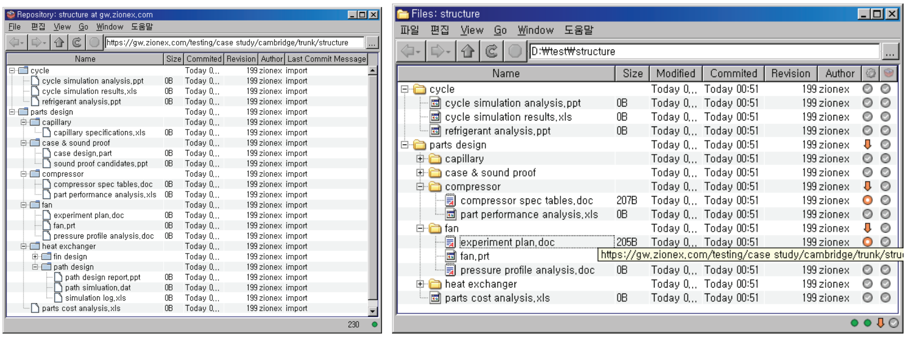

Figure 11. Knowledge Assets in the Repository and Local Working Directory

7. SOFTWARE

This study used IDEMS from Oculus Technologies Corporation (www.oculustech.com), groupware from Zionex (www.zionex.com), and Subversion from Tigris (subversion.tigris.org).

Integrated Development Environment for Modeling and Simulation (IDEMS) is a suite of software for engineering and design projects. The IDEMS Revision Manager client software provides a graphic, drag-and-drop user interface for interacting with Subversion repositories. The IDEMS Revision Manager server software includes Subversion, Apache, and NIS/LDAP authentication modules. A web-based server console provides drag-and-drop ease-of-use for managing access, monitoring repository use, and administrating the server. IDEMS also includes a web-based project portal with embedded components that scrape the repository to provide up-to-the-minute status on project performance and progress.

8. CONCLUDING REMARKS

Product design and development is a complex process requiring the extensive use of knowledge assets and effective communications amongst stakeholders. In this study, the lifecycle of progress in a project is viewed in five categories. With the perspective that the communication in projects is in general associated with decision making factors, capturing those factors generated from design knowledge assets of individual work environment and seamlessly sharing them with other stakeholders will make the communication more effective and thus expedite the process.

A computer-based solution to facilitate this concept and on-going projects were introduced. This solution is aimed to reduce communication errors in a product design and development project by effectively capturing and sharing key factors of decision decisions across the different levels of work environments as well as efficiently managing design knowledge assets.

REFERENCES

[1] Ulrich K. and Eppinger S.D. *Product Design and Development*, 1995 (McGraw-Hill)
[2] Nasr E.A and Kamrani A.K. *Computer Based Design and Manufacturing*, 2007 (Springer)
[3] Jung H.J., Hong D.S., etl. *Arthur D Little - Key Notes in R&D Management*, 2006 (Arthur D. Little Korea, in Korean)
[4] Burton-Jones, A. *Knowledge Capitalism: Business, Work, and Learning in the New Economy*, 1999 (Oxford University Press)
[5] Hazelrigg G.A. *Systems Engineering: An Approach to Information-Based Design*, 1996 (Prentice Hall)
[6] Wallace D.R. *A probability specification-based design model : applications to search and environmental computer-aided design*, 1995 (Doctoral Thesis, MIT)
[7] http://subversion.tigris.org
[8] https://support.oculustech.com/revmgr/intro