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R&D of CAD Systems Suitable for Japanese Design Organization Structure

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1 Introduction

Manufacturing technology was one of the priority fields defined in the government's Second Science and Technology Basic Plan. This field was renamed "MONODZUKURI (Value-creating manufacturing, technologies that increase the value of manufactured products) technology" in the Third Science and Technology Basic Plan, which was approved by the Cabinet on March 28, 2006. For the MONODZUKURI technology field, as one of the eight fields identified as requiring national effort, a promotional strategy has been formulated by the Council for Science and Technology Policy. This renaming represents the government's determination to enhance Japan's capacity for value creation-oriented manufacturing, which goes beyond traditional manufacturing technology, for the purpose of developing science and technology that can raise the value of products[1]. For Japan to maintain its international competitiveness and to further develop its economy under the constraints of resources, the environment and population, questions of how to form a value chain around 'MONODZUKURI' to encompass even service and information industries, and how to maximize the added value created in such a chain represent major policy challenges.

The value produced by the manufacturing sector accounts for around 20% of Japan's GDP. However, the fact that this added value represents as much as 90% of exports from Japan suggests that the manufacturing sector is more competitive than any other industry in Japan[1, 2]. The strength of Japanese-style MONODZUKURI is said to lie in the team-oriented approach combined with integration (known as 'suriawase' in Japanese), which allows talented engineers and technicians involved in a project to work together toward fine-tuning parameters in a cooperative work environment[1]. If we focus for a moment on manufacturing processes, products can be divided into two types: Modular Architecture products*1, as typified by desktop computers, and Integral Architecture products*2, as typified by automobiles. Research shows that Japan's manufacturing sector is more competitive in Integral Architecture products[3]. In a questionnaire given to publicly listed manufacturing corporations, as many as 70% of the respondents answered that their core business comprises of Integral Architecture products[3], suggesting that many listed manufacturers are internationally competitive in their core business segments.

The Third Science and Technology Basic Plan outlines a promotional strategy for each priority field, and in the case of the MONODZUKURI technology field[1] the significance of design and manufacturing systems is emphasized in its basic policy, entitled "Science-Based Japanese-style MONODZUKURI": "To remain internationally competitive in MONODZUKURI, the Japanese-style MONODZUKURI should not depend only upon the high management capabilities and skills of individuals, but should rather be further encouraged by promoting science and technologies adapted to the needs which exist in this field, such as constructing design and manufacturing support systems customized for specific manufacturing processes"[1].

One of the key strategic science and technology areas chosen to be promoted in the field of MONODZUKURI technology is "science-based KASHIKA technology that further advances Japanese-style MONOZDUKURI technology." In other words, the government has set out a policy for the dissemination and accessibility of MONODZUKURI by using information technologies and measuring/analysis technologies, in an effort to develop a scientific infrastructure for MONODZUKURI that can enhance Japan's strength in this area[1]. Information technologies that can create a database of products, storing design results, will play the central role in the building of support systems for design and manufacturing. Among such technologies are the computer-aided design (CAD) systems, the importance of which is currently under discussion by the MONODZUKURI technology Promotion Project Team on the Expert Panel on Basic Policy, part of the Council for Science and Technology Policy[4]. The team recognizes "promoting fundamental technologies for MONODZUKURI with the utilization of IT" as a primary issue in developing common fundamental technologies[1]. Another critical R&D issue identified is "new measuring/analysis technologies and appliances, and precision processing technology that meet MONODZUKURI-related needs," which the team suggests should be considered in connection with the previous issue of "promoting fundamental technologies for MONODZUKURI with the utilization of IT"[1]. In other words, they point out the need to address measurement issues in relation to CAD systems as processors of design information, if "the dissemination and accessibility of MONODZUKURI" is to be achieved through the specification of certain points of measurement and the verification of actual measurement data against design information[4]. In this way, CAD assumes a critical role in science-based MONODZUKURI in Japan[1, 4].

With these perspectives in view, this report clarifies the future direction of CAD technologies suitable for Integral Architecture design organization and structure, which represents the greatest strength of the manufacturing sector in Japan, and identifies those major issues which require national policy support to ensure that the manufacturing sector in Japan maintains and improves its international competitiveness.

2 Current usage of CAD systems

Figure 1 shows the position of the design process in the workflow of a manufacturer and the elements that make up the entire process. Manufacturers began utilizing CAD technologies in their design process around 1980, with the aim of increasing the competitiveness of their products. Since then many measures have been implemented to improve the designers' performance through the utilization of the information processing power of CAD systems.

The rate at which CAD technology has been utilized in the design process is cited in the White Paper on MONODZUKURI 2006[2] from "Research and Survey on Small and Medium Manufacturers' Deployment and Utilization of IT"[7], a report published by the Japan Industrial Policy Research Institute in March 2006. This source document divides CAD systems into three distinct categories, and reports that utilization rates among small and medium-sized manufacturers for these categories are 82% for two-dimensional (2D) CAD systems*3, 58% for three-dimensional (3D) CAD systems*4, and 33% for CAE systems*5. Another research paper on CAD utilization[8], which is based on a survey conducted in the autumn of 2002 and was presented by Fujita et al. to the Japan Society of Mechanical Engineers in January 2006, estimated that over 90% of manufacturers use CAD systems across the automobile, industrial equipment and general electric machinery industries. This implies that the adoption of 2D and 3D CAD systems and CAE tools among large companies is as least as common as among small and medium-sized companies, if not more frequent.

As Figure 1 shows, 2D/3D CAD and CAE systems play a core role in the detailed design and testing & trial production phases, although they make no contribution to the planning and concept design stages. The use of CAD/CAE systems for planning and concept design is limited to their utilization as peripheral work

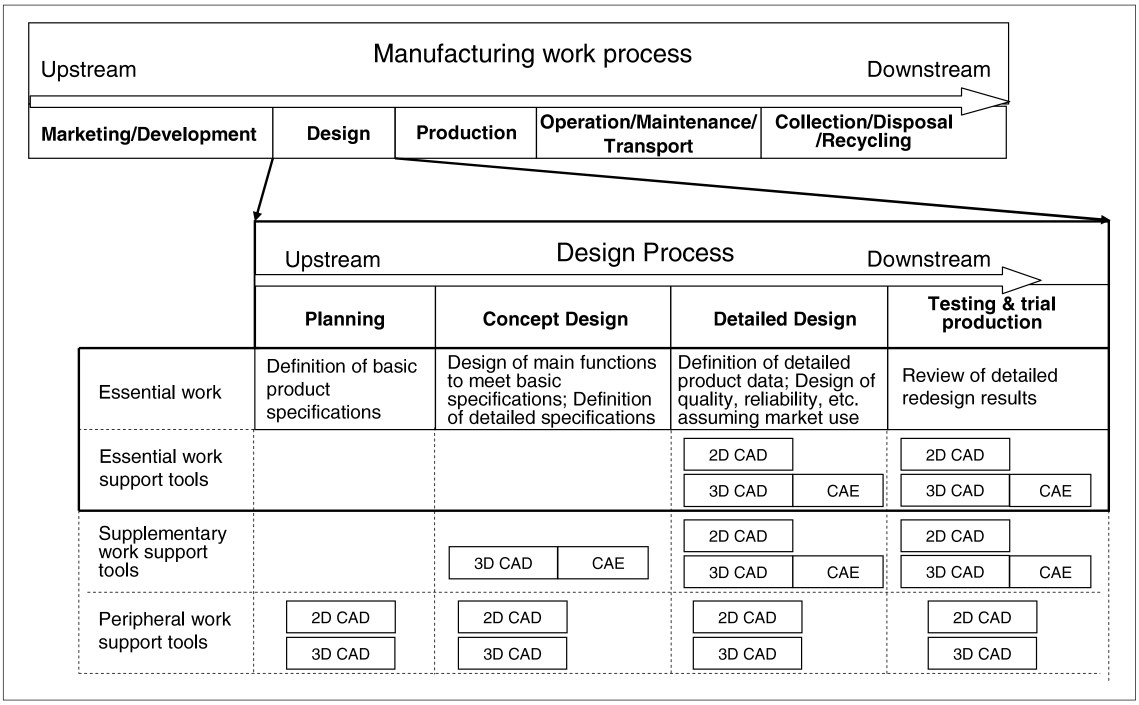

Figure 1 : Elements of the manufacturing work process and the design process

The above manufacturing process names are prepared by the STFC, based on the discussion frame for “10. Manufacturing field” in “The 8th Science and Technology Foresight Survey: Delphi Analysis”[5].The above design process names are prepared by the STFC, based on the report on standardization activities concerning the Design Process Assessment Indices[6], published by the Technical Standardization Center of the Technical Standards and Engineering Department, the Japan Electronics and Information Technology Industries Association (JEITA).

tools, helping designers to organize ideas and note the results of designs, or to their utilization as supplementary work support tools to assist in rendering the geometry of the main parts in three dimensions and estimating configuration spaces. The reason for such limited usage is that 2D/3D CAD and CAE systems are not designed to of handle the data necessary for product modeling, which is used the core work domain of planning and concept design.

The product model determines the structure of the database to be constructed for the product. In Figure 2, CAD applicability is defined from two perspectives: the type of data necessary for the product model and the stages constituting the design process. In other words, the chart illustrates four CAD applicability areas (S1 to S4) in terms of what kinds of data are essential for each design phase and how those data are used for design. The 2D/3D CAD and CAE tools available in today’s market would all be placed in the S4 category, which spans from the last part of concept design to detailed design and the testing & trial production stage. These systems can handle geometry[*6] as well as certain kinds of attributes[*7]. Meanwhile, current technologies have not succeeded in developing any practical CAD systems that can be used in the S1 or S2 areas. This explains why there were some blank areas for support tools in Figure 1. Although a CAD system may be used in the planning or concept design phase, its use is limited to supplementary or peripheral work, and does not extend to essential work.

Figure 3 shows how geometry, attributes and design intent[*8] are related to CAD capabilities. The 2D CAD system primarily handles geometric data, and its geometry creation function draws objects one-by-one that combine a triangle and a rectangle. The 3D CAD system works in the same way, and in principle the operator needs to create objects one-by-one. CAD systems that can automatically reshape an object when the dimensions are changed, using relations such as those shown as examples of attributes, are slowly becoming available. Systems that can also handle design intent are however still at the development stage[9]. To summarize, then, current CAD systems, which are designed mainly for geometric modeling and are therefore suitable for precisely modeling a component according to its geometric definitions, can accurately communicate

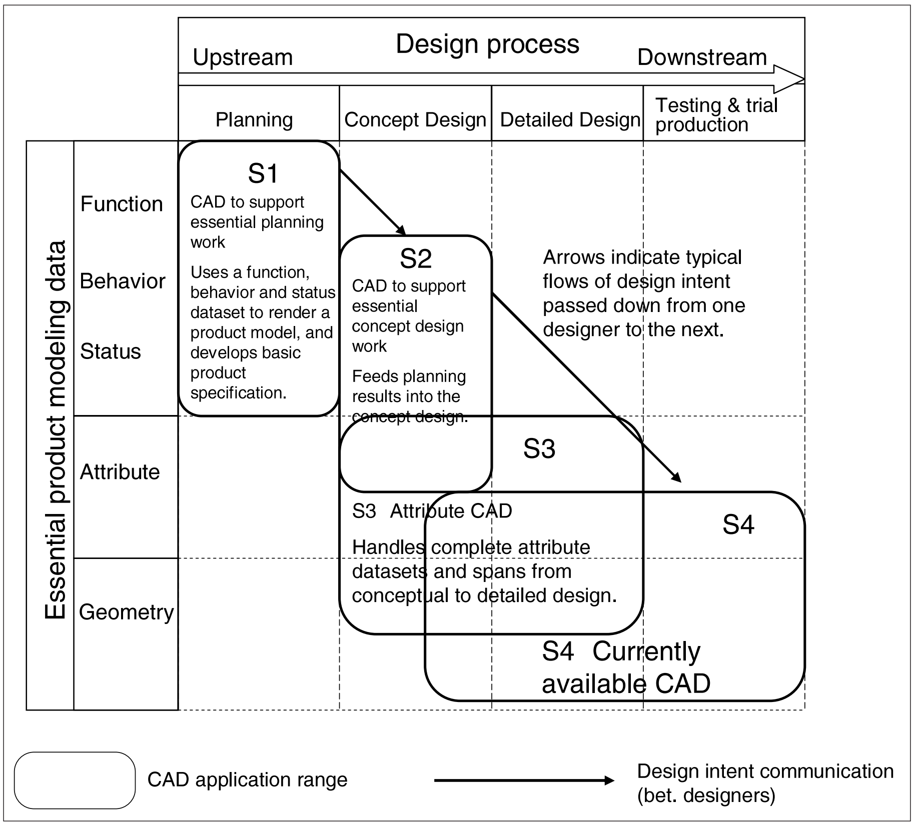

Figure 2 : Design process and CAD

Prepared by the author based on the results of joint research with Prof. Arai and his assistants Tsumaya and Wakamatsu, the Graduate School of Engineering, Osaka University, and Prof. Sugimura, the Graduate School of Engineering, Osaka Prefecture University.

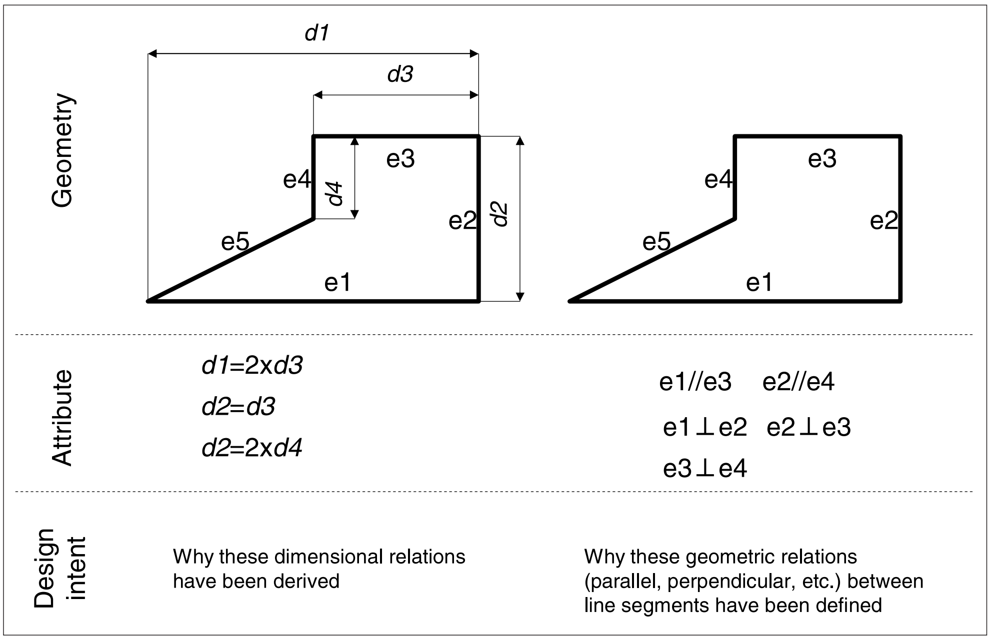

Figure 3 : CAD system function and processable data

geometric data to later processes[9-11].

Figure 4 demonstrates an example of the application of CAD to an electrical equipment unit, in an attempt to make CAD applicability to design easier to understand. The chart shows the application of both 3D CAD and CAE systems, described as essential work support tools in the detailed design phase in Figure 1. Figure 4 shows how a unit of electrical equipment (H15cm × W60cm × D40cm) is modeled by a computer and displayed on the screen. When the designer plans the layout of parts, there are a number of design

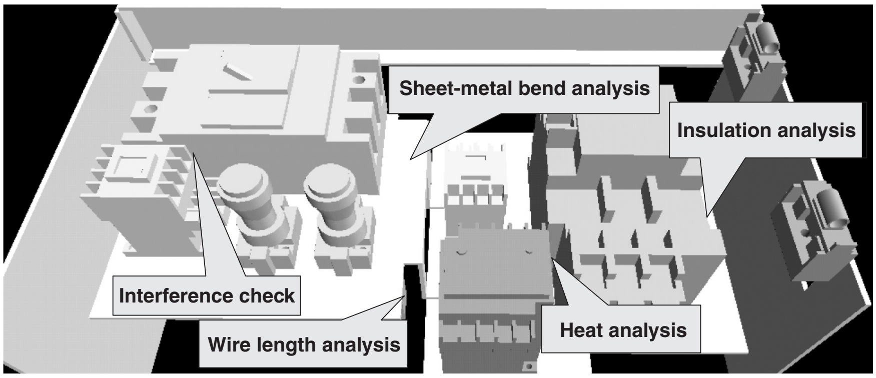

Figure 4 : Example of CAD application to electrical equipment unit

elements that must be taken into consideration, including interference checking, which refers to the spatial feasibility of the layout, as well as insulation, heat, and the required distance between parts. CAE and 3D CAD systems check these design requirements and suggest layout modification options to support the design process.

CAD systems are useful not only as individual design tools for designers, but are also often used at design review meetings held by review teams consisting of some 10 people. For example, together with the representation shown in Figure 4, a CAD system can make accessible information on the electrical fields and heat distribution which cannot normally be seen, and can display them on a large screen, helping the team to examine the design more closely.

3 CAD systems that can enhance the strength of Japanese-style MONODZUKURI

This chapter specifically describes the challenges faced in the development of IT systems that can further advance Japanese-style MONODZUKURI technology in the future.

3-1 Utilizing CAD systems in planning and concept design for making more competitive products

Many designers believe that CAD systems would bring substantial benefits if they could be utilized in the planning and concept design phases of the design process, because it is in these phases that decisions are made about the inclusion of certain characteristic features and functions into the product (those elements that give a product a unique competitive advantage). Eliminating as many problems as possible in the early stages of design is known as "front loading,"[2, 7, 12] and this approach plays a critical role in the management strategy of some companies. In particular, Japanese organizations often address inter-departmental design issues, such as ease of installation, serviceability, quality requirements, and the creation of a structure that facilitates easy assembly and thus higher productivity, in their planning or concept design phases[4, 7].

The range of applicability for the most popular CAD systems used currently (S4 in Figure 2) is not a result of strategic decisions by individual companies. CAD application is confined to the S4 area only because the mathematical product models that these CAD systems can handle are able to express geometry and attributes only partially. This is why current CAD systems are only applicable to design issues that can be reduced to purely geometric or spatial problems in mathematics. Figure 4 is a typical example of this. In other words, CAD application is limited to the production of drawings, simulation-based strength evaluations, and structure validation by displaying a 3D computer graphic model of a 3D geometric design. At the same time, CAD systems which would fall under the S3 category in Figure 2 are being developed by CAD manufacturers who have developed S4 CAD packages, largely by extending the current S4 applications. Once these become available, S3 CAD systems are expected to serve as useful transitional tools until S1 and S2 systems are developed.

S1 and S2 CAD systems that can be applied to planning and concept design must be enabled to express the product's "function, behavior and status"*9 by mathematical models. If S1 and S2 CAD systems were commercially available, a designer would start planning using an S1 CAD system. Then the data set by the S1 CAD system on the product's function, behavior and status would be passed to the S2 process. The designer would then conduct concept design using an S2 CAD system and successfully generate major attributes. These attributes would be transferred from the S2 to the S4 system. Finally, the designer would proceed to the detailed design stage with the help of an S4 CAD system, and use this to define detailed attributes and geometry. The design process would be completed by performing experiments and prototyping, using an S4 CAD tool.

To make such a workflow a reality, future R&D activities should be focused strategically on CAD systems applicable to the S1 and S2 areas.

3-2 Complete separation of the CAD system's data from the software used to analyze this data, and the need for small custom CAD software components

There is a concern that newly industrializing countries may quickly catch up with Japanese industry if CAD systems in the S1 and S2 categories as shown in Figure 2 are developed and distributed worldwide as powerful support tools in the planning and concept design phases, the critical phases in defining the product's unique and therefore most competitive features. In one case, Japan was actually outperformed by a less developed country which had strategically utilized special CAD systems in standard mold production. There are also other examples in which the widespread use of CAD systems enabled certain countries to imitate Japanese design technologies[10].

One possible solution to this concern, that the availability of CAD systems applicable to planning and concept design may inhibit Japanese companies from maintaining their strength, is to completely separate the CAD system's data from the software which carries out the necessary calculations. Some researchers have even suggested that there is a need to split the structure of IT systems into the following three categories, in an attempt to create IT tools most suitable for Japanese-style MONODZUKURI: (1) existing tools such as CAD systems, (2) common middleware that provides fundamental functions in Japanese-style MONODZUKURI, and (3) customized technological know-how unique to each company[7].

In the case of Figure 3, 'data' here refers to dimensional relations and geometric constraints (parallel, perpendicular, etc.). When these data are input, the software, which generates a draft object, is functioning like an 'engine.' The software then does not contain within it critical design results like dimensional relations. If the architecture of a CAD system could be clearly divided into part consisting of the 'engine' or software, and the part consisting of the data, then even if widely distributed only the software would be treated as a shared module among users and incorporated into a general-purpose CAD product, without the need for relevant data to be released outside the original organization.

In reality however, it is generally believed that complete separation between the software and data would not be possible in the majority of cases. This raises the need to develop small CAD software components that are customized for each type of object to be designed and that may be added to general-purpose CAD systems. Although enabled to deal with company-specific design technologies, these small CAD software components would be much smaller than the whole CAD system. Further, they would of course be used only within the organization. Engineers skilled in applied mathematics would be necessary for the development of these small CAD software components, in order to mathematically define the product modeling which constitutes the very core of every CAD system. This is because development would most likely make use of CAD development tools designed by CAD manufacturers. In other words, despite dealing with only one component, the level of technical capacity required for development is equal to that necessary in developing an entire system. However, Japan has seen a gradual decline in the number of engineers with sufficient expertise in applied mathematics to develop CAD software. Steps should be taken to increase the number of engineers specialized in applied mathematics needed for product modeling.

3-3 CAD systems to support design processes that require frequent communication across organizational boundaries

It is said that CAD systems developed in Western countries are inherently not suited to Japanese organizations. One reason given is that the standards to which Western CAD manufacturers design their products have been formulated on the assumption that it is Western organizations that will be using these products. Western organizations tend to divide work among sections very clearly, define areas of responsibility much more specifically, and their members are not required or expected to communicate across organizational boundaries. As such, they can differ somewhat from Japanese design organizations. Such differences were discussed by the MONODZUKURI technology Promotion Project Team on the Expert Panel on Basic Policy, the Council for Science and Technology Policy, as an issue to be considered in the field of IT for MONODZUKURI[4]. In the same context, survey reports published early in 2006 concluded that CAD systems developed in Europe and North America are not suitable for Japanese organizations, based on the opinions of CAD advocators in several companies[7, 9].

The CAD systems developed in the West that have been indicated as being unsuitable for Japanese organizations[4, 7, 9, 10] are CAD packages that are in use in the S4 category in Figure 2. It is possible that this lack of suitability is true for not only S4, but also for the S1 to S3 categories.

In both Japanese design organizations and in their activities, designers usually look at the entire design process, including its downstream phases. Meanwhile, downstream process designers send important feedback on quality improvement and other issues to upstream process designers. The design activities are consistent throughout the organization because of frequent communication across organizational boundaries. The result is the creation of values, such as improving product quality, which is regarded as the strength of the Japanese manufacturing sector[1, 3].

Any design, whether it represents product shape or other elements, is a result of selection from multiple choices. It is essential to let the engineers in downstream processes know why that particular shape has been chosen by the designer. Similarly, an engineering change in an upstream process requires the downstream process teams to be notified, without fail, of the content of and the reason for the change. This information is “design intent,” and it is of a different nature to function/behavior/status, attributes and geometry (Figure 3). The arrows in Figure 2 indicate typical flows of design intent being passed down from one designer to the next. CAD systems should be equipped with a mechanism for these flows. This kind of communication between designers, which is very common in Japanese organizations, is the strength of Japanese-style MONODZUKURI, and should be incorporated into CAD systems.

For example, let us assume that a chain-driven machine that will assist a person to travel is to be designed. Let us also assumer that the designer chooses as thin a chain as possible within the permissible range for safety, only from the perspective of rationalizing the design. However, in terms of maintenance of the machine, using the thinnest chain in the design may result in a tight tolerance for chain tension and thus longer time for adjustment. The consequence of this is an increase in total cost. In a case such as this, a Japanese designer would communicate with the maintenance section in the early stages of design and would be able to choose a chain that is a little thicker than the absolute thinnest, and thus a little more robust, thereby reducing the total cost.

Even Western CAD manufacturers have developed various related applications for CAD systems that are meant to support cross-departmental design teams. Typical examples are product data management (PDM) systems and networked design review systems[7]. These systems are effective design data management tools aimed at supporting any design process which comprises of multiple separate sections by allowing them to access synchronized design data or by creating electronic databases that can still be used in 10 years time. Although these are both effective within Japanese organizations, design data management and inter-departmental communication are still two different functions.

In short, CAD systems to support inter-departmental communication should ideally consist of an integrated software package that allows engineers in the design process to handle problems in production, maintenance and other downstream processes. The passing down of design intent as represented by the arrows in Figure 2 is an important means of communication and should therefore be incorporated into CAD systems.

It also must be noted that an integrated CAD package would require a large-scale development project (and consequently a system of an equally large scale).

4 Current CAD research in Japan

Most of the research papers published on CAD before 1990 fall within the S4 category in Figure 5. Many of them addressed equations that can serve as complete mathematical representations of the three-dimensional shapes of objects or equations for curved surfaces (e.g., of cars and aircrafts) that cannot be represented by a single polynomial. These research fields are known as the solid modeling theory and the free-form curved surface representation theory respectively. There was also active research in numeric analysis to convert these theories into formats that could be processed by computers. Although basic equations for these two theories had almost been completed by around 1970, application to complex real-world products had to wait for further advances in research. Many papers on advanced versions of the basic equations were published around 1990. They were aimed at mathematically defining product shapes. Theoretical problems in the basic equations were outlined in a number of articles[13-15] released around 1982, which were later cited by many papers. Since 1990, the focus of research among CAD system developers shifted to the question of how to improve basic equations to achieve higher

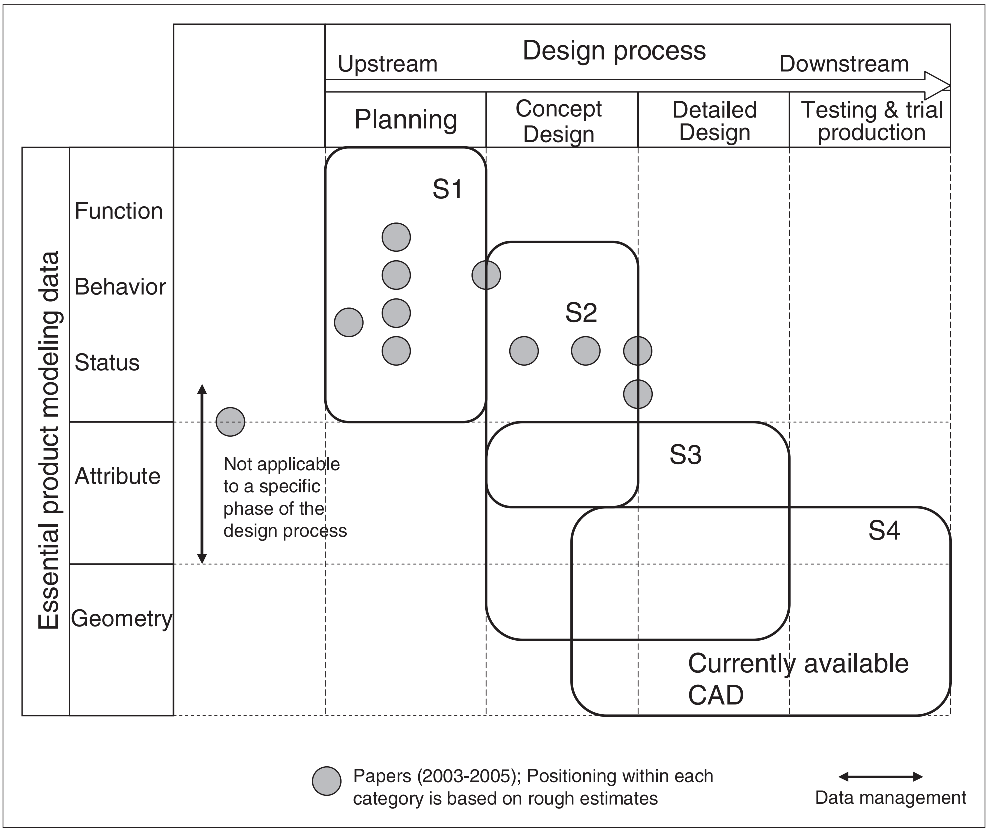

Figure 5 : Design engineering research trends as demonstrated by papers

Recent papers are plotted on Chart 2 by topic.
Prepared by the author based on the results of joint research with Prof. Arai and his assistants Tsumaya and Wakamatsu, the Graduate School of Engineering, Osaka University, and Prof. Sugimura, the Graduate School of Engineering, Osaka Prefecture University.

processing speed and thereby higher system performance. By 2000, the subjects of papers were distributed among all the categories from S1 to S4.

A typical paper on S1 and S2 is Reference[11], which attempts to develop a theory to represent a product model on a computer, using data related to function/behavior/status and intent. This kind of research requires an approach that is unlike the one taken in S4 research, or research that aims to mathematically express 3D geometric data, since function/behavior/status and intent are non-geometric data. The titles of papers in the S1 and S2 domains often include terms such as “the designer’s thinking process,” “design process with intent,” and “knowledge base.”

Recent Japanese papers focusing on the design process, like the one mentioned above, are plotted in Figure 5. Although there are many papers dealing with this topic, analysis was based on discussions held with Professor Arai and members of his laboratory at the Graduate School of Engineering, Osaka University, and with Professor Sugimura, at the Graduate School of Engineering, Osaka Prefecture University. The keyword used for the analysis was not “CAD” but “design engineering.” The following criteria were adopted for the analysis.

(1) The analysis shall cover the papers published in and after 2003.
(2) Papers focusing on specific design areas, such as shipbuilding and construction, shall be excluded. For this reason, the main targets of the analysis shall be those papers submitted to the Japan Society of Mechanical Engineers, the Japan Society for Precision Engineering, and the Japanese Society for Artificial Intelligence.
(3) The authors shall be persons continuously engaged in design system research.

Only 11 papers were found to satisfy the above criteria. The results clearly show that recent papers concentrate on the S1 to S3 categories rather than on S4.

The analysis has also revealed that Japan is the center of research for formulating product modeling theory applicable to planning or concept design. However, the number of researchers, including university professors, who are continuously engaged in such research is small, at a little over 10. The number of researchers in firms and other private-sector organizations, which is difficult to calculate because many of these researchers address this topic only temporarily, probably stands at less than 10, if only those who specialize in theoretical research are counted. This number is very small considering the size of Japan’s industry. Some of the authors of the papers analyzed and the professors who lead this field assume that the establishment of a theory applicable not only to specific design cases, but also to a wide variety of practical design projects, depends largely on future theoretical research.

Although no statistics are available on the number of researchers engaged with CAD, the number is far smaller in Japan than in Western countries, and it is further said that the numbers of such researchers has sharply grown in recent years in South Korea, China and Taiwan. This is demonstrated by the fact that the authors from these Asian countries have come to account for 70-80% of the papers submitted to CAD-related journals.

Traditionally, most R&D funding for CAD systems has been spent on software development. However, future funding programs should focus more on nurturing researchers who can contribute to establishing product modeling theory. There are only a few universities in Japan that offer courses in applied mathematics as a fundamental theory for product modeling. Strategic assistance should be provided in this area, in view of the issue identified out in Section 3-2-the need to increase the number of engineers with expertise in applied mathematics.

5 Conclusion

In summary, this article highlights four issues to be addressed in relation to computer-aided design (CAD), which is an element of the “technology for science-based dissemination and accessibility of MONODZUKURI that further advances Japanese-style MONODZUKURI technology,” a key strategic science and technology area as chosen in the MONODZUKURI technology field in the Third Science and Technology Basic Plan.

(1) The design process consists of, in descending order, workflow of planning, concept design, detailed design, and testing & trial production phases. CAD systems applicable to the planning and concept design phases, in which functions which will give products their competitive edge are defined, need to be strategically developed.

(2) Uniform design activities enabled by frequent communication across organizational boundaries, which are said to be a strength of the Japanese manufacturing sector, will remain the driving force of value creation, such as the further improvement of product quality. R&D focused on the creation of an integrated CAD system that enables the designer to consider issues concerning production, maintenance and other downstream processes, and that can handle data that allows engineers working on downstream processes to embrace the concepts behind the product structure as envisaged by the designer.

(3) There is a concern that the availability of CAD systems that support planning and concept design may prevent individual companies from being able to maintain their strength. One possible solution is to completely separate the CAD system's data from the software. This would suggest the need for R&D on CAD system architecture to prevent that data which represents the basis of a product from being released outside the organization.

(4) In Japan there are currently very few researchers specializing in the applied mathematics needed to establish product modeling theory, or engineers with expertise in such applied mathematics. Furthermore, there are only a small number of universities in Japan that offer courses in applied mathematics as fundamental theory for product modeling. Strategic support must be provided to these areas in the future.

Each of the issues identified above requires further detailed examination by experts.

Acknowledgements

The author would like to sincerely thank the following people for their valuable opinions: Professor Eiji Arai and his assistants Mr. Akira Tsumaya and Mr. Hidefumi Wakamatsu, the Graduate School of Engineering, Osaka University; Professor Nobuhiro Sugimura, the Graduate School of Engineering, Osaka Prefecture University; and Professor Hiromasa Suzuki, the Research Center for Advanced Science and Technology, the University of Tokyo.

Glossary

*1 Modular Architecture products

Products that are completed by carefully assembling existing pre-designed parts.

*2 Integral Architecture products

Products that can deliver expected functionality as a whole only when parts specifically designed and customized for them are fine-tuned to achieve harmonization.

*3 Two-dimensional (2D) CAD system

A system designed mainly to handle drawing data and produce drawings.

*4 Three-dimensional (3D) CAD system

A system designed to create three-dimensional geometric data so that designers can review design details, including geometric and layout interference problems, without the need to build prototypes.

*5 CAE (Computer-Aided Engineering) system

A system designed to support simulations in the design process.

- 2D CAD, 3D CAD and CAE are terms often used to classify those CAD systems currently available. In the broadest sense, 'CAD system' refers to a software tool that supports any part of the general design process, and the term is therefore often used as a collective term to represent both 2D and 3D CAD systems as well as CAE systems.

*6 Geometry

Data concerning vertices, line segments, areas and spaces. In Figure 3, geometry refers to an object consisting of square and triangle line segments.

*7 Attribute

Examples of attributes are material, surface roughness, physical properties, and tolerance. Attributes of a cable refer to what it is intended to transmit, such as signals or 200-volt electricity. In Figure 3, attributes are data on dimensional relations, and geometric relations (known as geometric constraints) between line segments, as expressed as parallel, perpendicular and so on.

*8 Design intent

This refers to product structure definitions and engineering changes which are made on the basis of the designer's concepts and the data on the process through which the designer has reached the specific conclusion. They are collectively called design intent.

9* Function, behavior and status

Their definitions are the same as in a non-technical context. Take the automatic revolving door as an example. Although the automatic revolving door offers many functions, one of them is "safe revolution." The behavior associated with this is "stopping instantly if something is caught, to ensure safety," and the status is either "revolving or motionless." This produces a dataset: "automatic revolving door; safety; stops if something is caught; revolving or motionless." The idea of expressing a product by a combination of its function, behavior and status was proposed in a report by Umeda et al[11].

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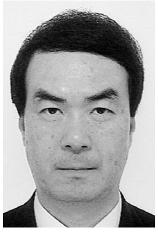

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(Original Japanese version: published in August 2006)