Highly Reliable CAE Model, the Key to Strategic Development of *New JIT*

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Abstract: In recent years, the advanced manufacturing industry is engaging in a "global production strategy – for simultaneous achievement of QCD". A close look at the development designing and production process stage reveals an excessive repetition of "experiment, prototyping, and evaluation" that prevents the "scale-up effect" generated in the bridging stage between prototyping, experiment, evaluation, and mass production. Consequently, what is urgently needed, is innovation to promote the advance from the conventional evaluation - based development, that uses the prototyping and experiment process which had long supported highly reliable designing, to a CAE prediction - based designing process. To accomplish this a new development designing technique was established, the "*Highly Reliable CAE Model.* This is the key to strategic promotion of the *"Total Integrated Development Design model - Advanced TDS"* which utilizes the core element of the *"Total Development System, TDS" of "New JIT*". In an effort to realize this, the author has proposed the "high quality assurance model for super short period development designing, a "*Highly Reliable CAE Numerical Simulation"* and demonstrated its effectiveness. As an application example, a simulation technology was developed for molding urethane foam and it was implemented as the "*Production of CAE Software for Molding Automotive Seat Pads -Urethane Foam Molding Simulator*".

Key words: *New JIT, TDS, Advanced TDS, Highly Reliable CAE Model, Highly Reliable CAE Numerical Simulation,* Molding Automotive Seat Pads, *Urethane Foam Molding Simulator*

1. Introduction

In recent years, the automotive industry is engaging in a "global production strategy – for simultaneous achievement of QCD (quality, cost, and delivery)"aiming to achieve "worldwide uniform quality and production at optimum locations," in an effort to prevail and survive in the "worldwide quality competition" [1]. One of the specific measures taken is an urgent improvement of intelligent productivity in the advanced manufacturing processes of planning and development, designing, prototyping evaluation, mass production preparation, and mass production for the purpose of offering highly reliable products to create customer value in a short period of time [2].

Among other things, a close look at the development designing and production process stage reveals an excessive repetition of "experiment, prototyping, and evaluation" that prevents the "scale-up effect" generated in the bridging stage between prototyping, experiment, evaluation, and mass production. Therefore, innovation of the development and production method, as well as reduction of the development period, is a top priority issue [2].

Against this background, the author focuses on the "Technical Requirements for High Assurance CAE (Computer Aided Engineering)" for establishing a development designing quality assurance system that is indispensable for CAE in the automotive industry. A prerequisite for automotive development and designing is to derive highly reliable CAE analysis results that show no gap between the actual machine lab tests and the analysis results.

To realize the rational integration of overall optimality and partial optimality needs to be achieved through the process of "problem – theory – algorithm – modeling – computer" as a technical requirement to be included in "highly reliable CAE software" [2].

For this reason, what is urgently needed, is innovation to promote the advance from the conventional evaluation-based development, that uses the prototyping and experiment process (a method based on the confirmation of real goods for improvement) which had long supported highly reliable designing, to a CAE prediction - based designing process. To accomplish this a new development designing technique was established, the "*Highly Reliable CAE Model*". This is the key to strategic promotion of the "*total integrated development design model*, *Advanced TDS*" which utilizes the core element "*Total Development System*, *TDS*" of "*New JIT*" [3].

In an effort to realize this, the author has proposed the "high quality assurance model for super short period development designing, a "*Highly Reliable CAE Model*" and demonstrated its effectiveness. The author explains a "*Highly Reliable CAE Numerical Simulation*" through the use of a concrete target. As an application example, a simulation technology was developed for molding urethane foam and it was implemented as the "Production of CAE Software for Molding Automotive Seat Pads - *Urethane Foam Molding Simulator*" [4].

2. Background – Management Tasks of Advanced Companies

Amidst severe global competition for survival in Japan and abroad, manufacturers must again recognize the "ideal of quality management in the manufacturing industry". This is especially true when they see numerous instances in which quality problems critically damage customer satisfaction. Increasing recalls by a number of advanced companies that should be leading the world in global production indicates the need for reinforcement of the "managerial engineering capabilities" of manufacturers in creating highly reliable products [5-7].

For the reasons stated above, the author conducted a consciousness survey covering the directors and upper-class managers of eighteen advanced companies (225 subjects in total, including Toyota, Denso, Aishin-Seiki, Fuji Xerox, NEC, Daikin-Kogyo, JFE Steel, and

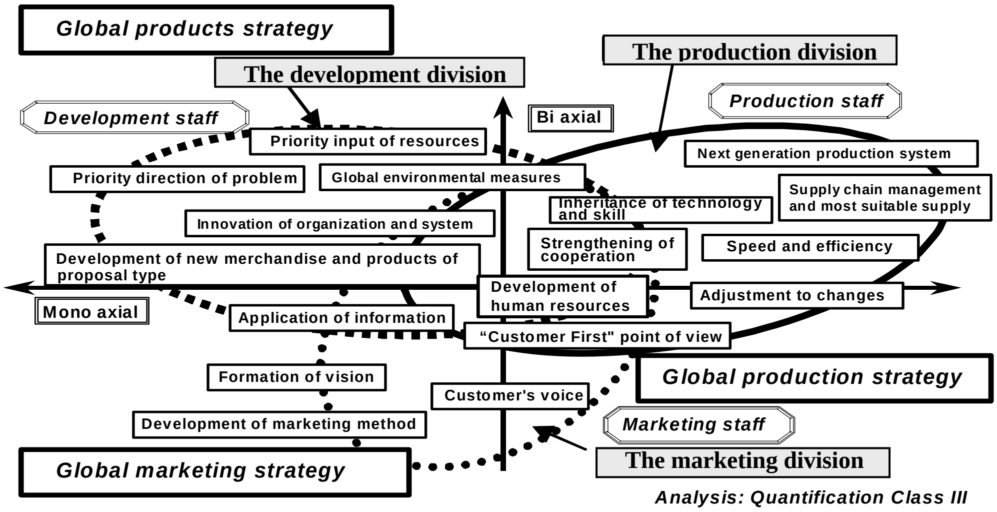

Figure 1 Management Technology Problems throughout the Advanced Companies (Positioning of Opinion)

others) [3, 8]. As shown in Figure 1, general management technology problems have been pointed out utilizing Quantification Class III. The figure indicates that the top priority issue of the industrial field today is the "new deployment of global marketing" for surviving the era of "global quality competition".

The pressing management issue, particularly for advanced manufacturers to survive in the global market, is the "uniform quality worldwide and production at optimum locations" which is the prerequisite for successful global production [9-11]. To realize manufacturing that places top priority on customers with a good QCD and in a rapidly changing technical environment, it is essential to create a core principle capable of changing the technical development work processes of development and design divisions [5]. Furthermore, a new quality management technology principle linked with overall activities for higher work process quality in all divisions is necessary for an enterprise to survive [3, 7, 9, 10].

3. The Need for a New Global Development Design Model for the *New JIT* Strategy

3.1 Significance of *New JIT,* Management Technology Principle

Customers today select products that fit their lifestyles and sense of values, and question "*company reliability*" in terms of product reliability (quality and value for use). In order to manufacture attractive products as an advanced company, it is now necessary to establish a principle of new management technology for the next generation that will serve as a systematic and organizational behavioral principle to achieve a higher linkage of the business process cycles of all divisions, including not only sales, development and design and manufacturing, but also indirect divisions such as administrative/clerical, and suppliers.

Based on these needs, the authors [1, 2, 5] proposed a new principle for next-generation management technologies - *New JIT,* as shown in Figure 2. The hardware systems of *New JIT* are *TDS (Toyota Development System), TPS (Toyota Production System) and TMS (Toyota Marketing system).* These core systems are indispensable for establishing new management technologies.

Further, the authors [7] have proposed a new principle of quality management called "*Science TQM*" (Total Quality Management by Utilizing "*Science SQC*" (Statistical Quality Control) called "*TQM-S*") by using a principle of quality management, *Science SQC*, as a software system that improves the quality of all divisions' business processes in developing strategic quality management, important for survival in the current environment of worldwide quality competition.

Based on the matters cited above, the authors [3] have been verifying the effectiveness of *New JIT* as a new management technology model to further develop "traditional *JIT*"

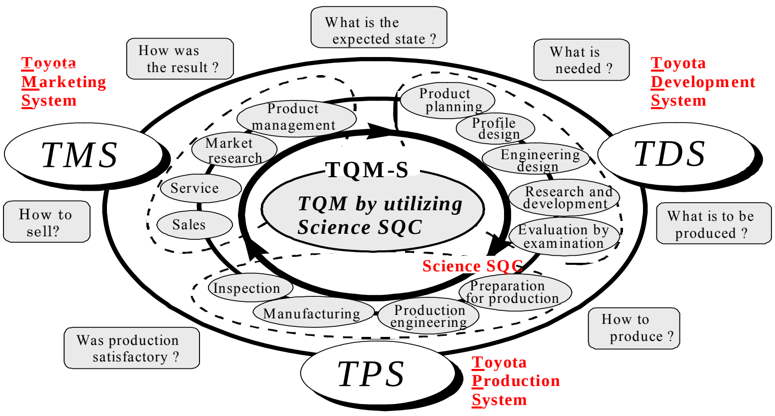

Figure 2 *New JIT*, Management Technology Principle

practices at an advanced company in Japan. Thus the author has tested the effectiveness of the "strategic model of new management technologies" for further advancement of *JIT* at Toyota and others [1, 5, 7, 9].

3.2 The Need for a New Global Development Design Model

At present however, advanced companies in the world, including Japan, are shifting to "global production" to realize "uniform quality worldwide and production at optimum locations" for survival in fierce competition [1, 2]. To attain successful global production, technical administration, production control, purchasing control, sales administration, information system and other administrative departments should maintain close cooperation with clerical and indirect departments while establishing strategic cooperative and creative business linkages with individual development, production and sales departments, as well as with outside manufacturers (suppliers).

Today when consumers have quick access to the latest information in the worldwide market thanks to the development of IT (Information Technology), strengthening of a development design that utilizes *TDS* has become increasingly important. "Simultaneous attainment of QCD requirements" is the most important mission for developing highly reliable new products ahead of competitors as shown in Figure 3 [3].

As shown in the Figure, the main elements are composed of (a) collection and analysis of both internal and external information focusing on the importance of design thought, (b)

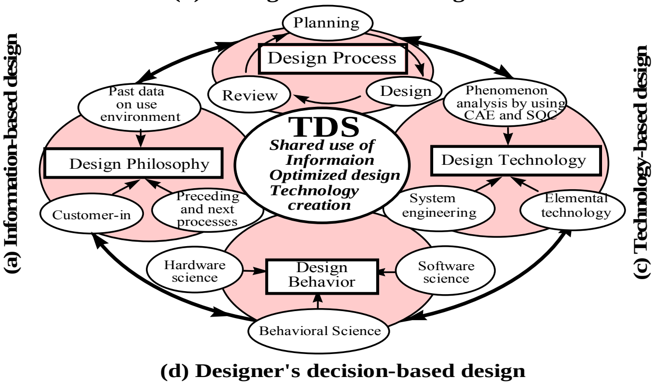

Figure 3 Schematic Drawing of "*TDS*"

design process development and its management, (c) design technology to create a general solution and (d) design guidelines (theory – action – decision making) to train designers.

Recently, the authors [3] have been verifying the effectiveness of proposed *TDS* at advanced corporations, including Toyota Motor Corporation. In order to manufacture attractive products, therefore, the author requires the urgent establishment of a "new global development design model" for the next generation.

3.3 *Advanced TDS*, Total Integrated Development Design Model

Currently, to continuously offer attractive, customer-oriented products, it is important to establish a "*new development design model*" that predicts customer needs [7, 8]. In order to do so, it is crucial to reform the business process for development design [1]. Manufacturing is a battle against irregularities, and it is imperative to renovate the business process in the development design system and to create a technology so that serious market quality problems can be prevented in advance by means of accurate prediction/control. For example, as a solution to technical problems, approaches taken by design engineers, who tend to unreasonably rely on their own past experience, must be clearly corrected.

In the business process from development design to production, the development cost is high and time period is prolonged due to the "scale-up effect" between the stages of experiments (tests and prototypes) and mass production. In order to tackle this problem, it is urgently necessary to reform the conventional development design process. Focusing on the successful case mentioned above, the authors [2] deem it a requisite for leading manufacturing corporations to balance high quality development design with lower cost and shorter development time by incorporating the latest simulation CAE and *Science SQC* [2, 12, 13].

Against this background, it is vital not to stick to the conventional product development method, but to expedite the next generation development design business process in response to a movement toward digitizing design methods. Having said the above, the authors [2] propose the "*Advanced TDS*, *Total Integrated Development Design Model*" as described in Figure 4, and further updates *TDS*, a core technology of *New JIT*. *New JIT* is aimed at the simultaneous achievement of QCD by high quality manufacturing which is essential to realize CS (Customer Satisfaction), ES (Employee Satisfaction), and SS (Social Satisfaction).

For realization, (1) customers' orientation (subjective implicit information) must be scientifically interpreted by means of "*Customer Science*" [3, 10], namely, converting the implicit information to explicit information by objectifying the subjective information using *Science SQC* so as to (2) create "*High reliable development design system*", thereby (3) eliminating prototypes with accurate prediction and control by means of "*Intelligence Simulation*".

To this end, it is important to (4) introduce the "*Intellectual Technology Integrated System*" which enables a sharing of knowledge and the latest technical information possessed by all related divisions.

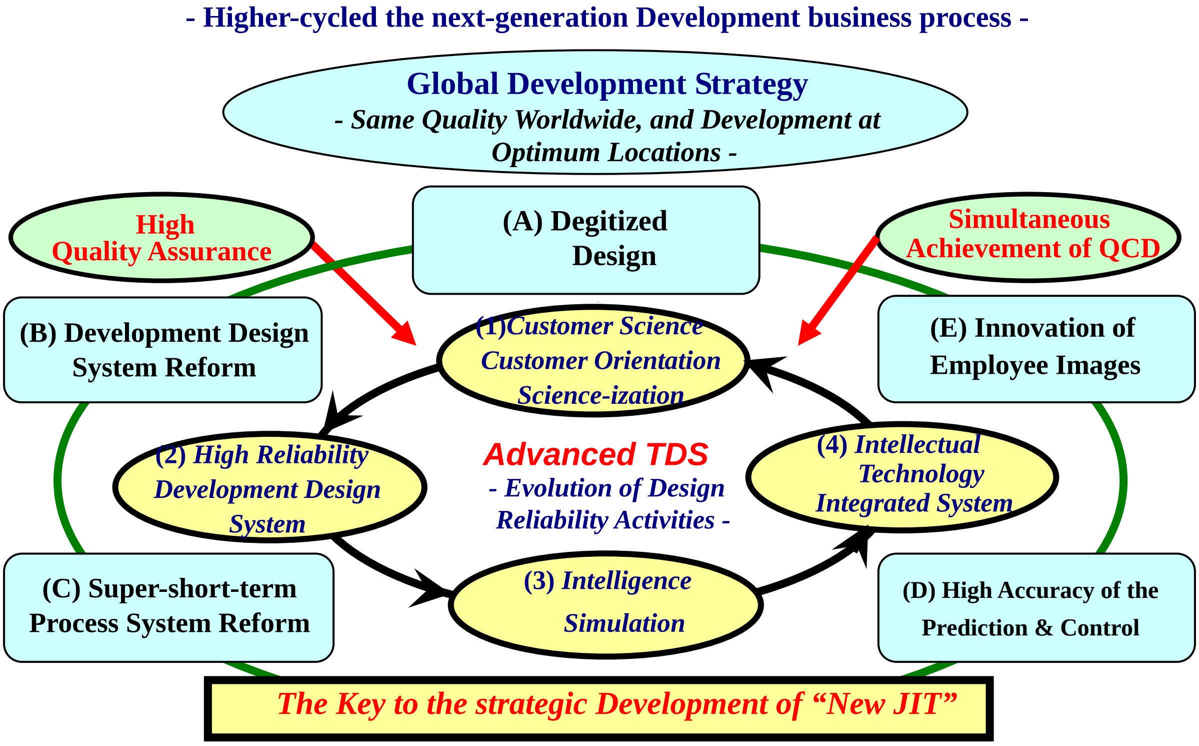

Figure 4 *Advanced TDS,* Total Integrated Development Design Model

4. Proposal of the "*Highly Reliable CAE Model*" Utilizing *Advanced TDS*

Investigation into the management technology issues concerning to managers and administrators of advanced corporations indicate that development designing puts primary emphasis on the technical problems in the process of finding a solution, and resources are concentrated on the pressing issue of developing new models and products on a proposal basis as shown in Figure 1.

4.1 Revolution in Manufacturing Development Design and the Evolution of CAE

The author takes the "Automobile" as a representative example of the manufacturing industry as shown in Figure 5 [2, 14]. The conventional process of automobile development/production (from planning to mass production) was carried out through the first and the second cycle of "experiment – prototyping – evaluation". As a result, it took approximately 40 months from the start of development to the beginning of mass production.

Recently however, the development production period of automobile development/production (from planning to mass production) has been further shortened from 2 years to one year, which includes the process of designing – prototyping – experimental evaluation – production preparation – mass production trial. This process is now anticipated

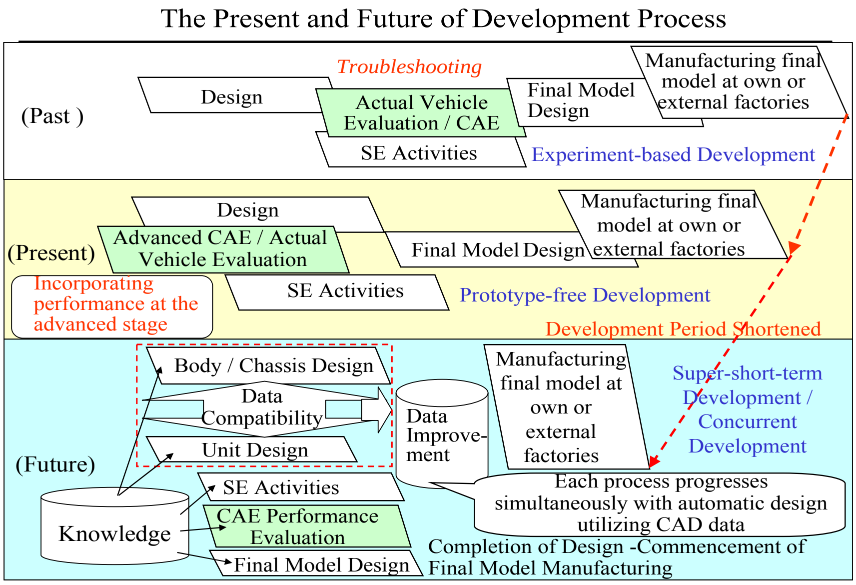

Figure 5 Effect of SE, CAD and CAE for Shortening Vehicle Development Term

by means of (1) SE (simultaneous engineering) activities, (2) advancement of CAD/CAM (Computer Aided Design / Manufacturing, 2D→3D solid) , IT (Information Technology), (3) introduction of, and a wider range of applications of CAE, and (6) the advancement of knowledge integration, cutting down the number of prototypes and overlapping stages in the "experiment – prototyping – evaluation" cycles required [1, 15].

Now, amidst severe competition and demand for time reduction in product development, what is normally called "rework" resulting from various production/quality related problems is virtually impossible. Against this background of intensifying competition, coupled with the shortage of development and design specialists, has been addressed by increasing CAE investment and bringing in an outsourced workforce. It has been observed, however, that because of insufficient development of training programs to foster highly skilled CAE engineers, the effectiveness of CAE has been weakened and the authors' development/design process aimed at simultaneous achievement has been hindered [15].

The authors [1] also grasped the effectiveness of as well as problems with CAE utilization and the importance of CAE education and technology succession through a case study of a leading corporation [16]. Also, studies by the authors have demonstrated the effectiveness of incorporating SQC, which expands the effectiveness of CAE and its range of application

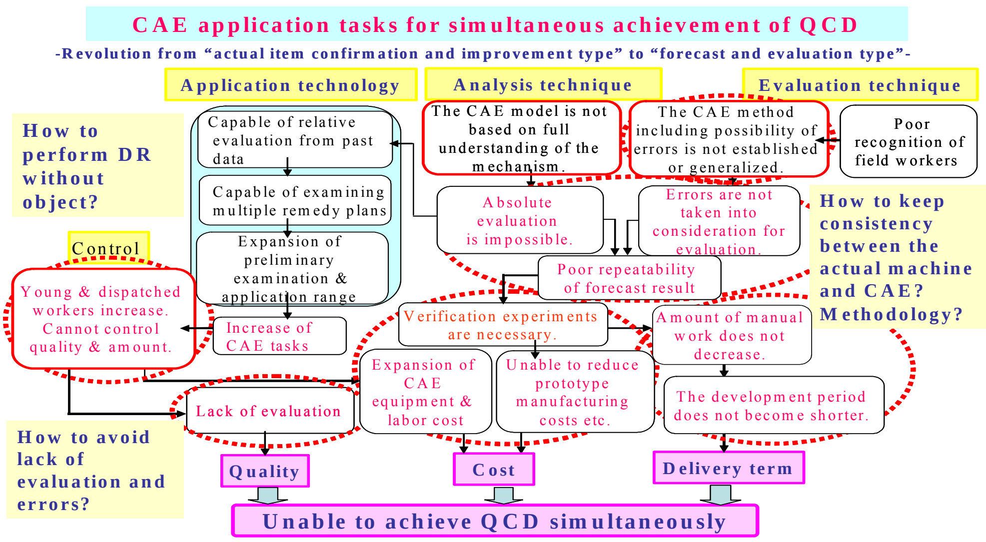

Figure 6 Issues When Applying CAE to Development Design Reform

[17-19]. Based on the above knowledge, the "impact of CAE and obstacles to be overcome" are plotted in the relation diagram from the standpoint of "CAE management and simultaneous achievement of QCD" which realizes the high quality assurance of automobiles as shown in Figure 6 [15].

By summarizing the diagram, it becomes clear that one of the problems in applying CAE for the realization of simultaneous achievement of QCD is the "failure to understand the mechanism of the technical problems encountered and apply it to a CAE model" [1]. The second point observed is that, as a substitute for prototypes and experimental evaluation, this CAE analysis proves to be insufficient for reliable prediction and control.

The gap (analysis error) between the analysis and the experimental evaluation data must be as much as a few percent, and at present, the "establishment of CAE software and its usage taking error into account" is not at a satisfactory level. Therefore, despite its expansion, CAE cannot be regarded as making a sufficient contribution to the simultaneous achievement of QCD and reduction in development time [15].

4.2 Proposal of the "*Highly Reliable CAE Model*" utilizing *Advanced TDS*

For this reason, what is urgently needed, is innovation to promote the advance from the conventional evaluation-based development, that uses the prototyping and experiment process (a method based on the confirmation of real goods for improvement) which had long supported the highly reliable designing, to a CAE prediction-based designing process. To accomplish this a new development designing technique was established, the "*Highly Reliable CAE Model*" *utilizing Advanced TDS.*

Therefore, the author discusses the "extraction of issues" with a view to creating the *Highly Reliable CAE model.* Next, the developers engaging in CAE (car body manufacturers – Hino Motors, Ltd. and Toyota Motor Corp., parts manufacturers – NHK Spring Co., Ltd., software makers - Mizuho Information & Research Institute, Inc., system developers –

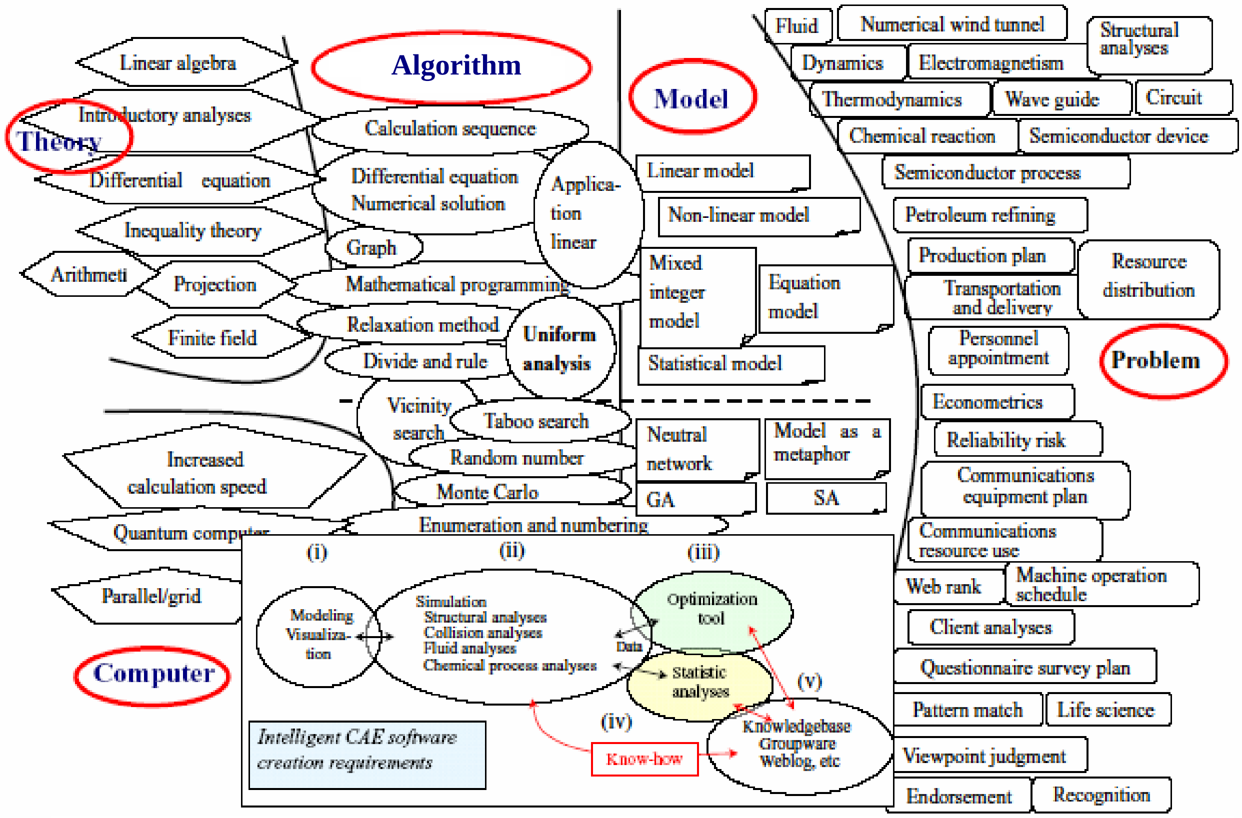

Figure 7 *Highly Reliable CAE Model* utilizing *Advanced TDS*
(Problem – Model – Algorithm – Theory - Computer)

Mathematical Systems Inc., Tsukuba Univ. and Aoyama Gakuin Univ., etc.) have jointly sorted out the free responses to the questions given and summarized the required technical requests as shown in Figure 7 [20].

This model illustrates the techniques belonging to the domains of (1) problem setting, (2) modeling, (3) algorithm, (4) theory, and (5) computer (calculation technology). These techniques are being used for the purpose of realizing the systemization or formulation of working level problems, development of the kind of algorithms which utilize calculation resources more efficiently, logical analysis of the algorithms, and improvement in hardware and software technology for accelerating the calculation speed.

These are the development targets for all kinds of new and old technologies related to computer science which have been actively promoted throughout the world. Far from intending to thoroughly cover the field, this figure simply lists some names of the main techniques in each domain, but it helps us to see the large number of options available for elemental technologies involved in CAE as we try to improve it.

However, from the standpoint of implementing CAE as a problem solving method on a working level, the sheer number of, and a wide selection of, these elemental technologies is not sufficient. This is because CAE is thought to be a process consisting of multiple elemental technologies. The process of CAE first starts with (1) setting of problems to be solved, as well as (2) modeling of these problems as some type of mathematical formula. In CAE, when using calculators as a means to analyze the model, such a means of analysis needs to be provided in the form of a calculation procedure, namely, (3) algorithms, so that the software can perform calculation. The validity, applicable range, and performance or expected precision of such algorithms themselves can be deduced from (4) some kind of theory. Needless to say, the technology related to the computer itself functioning as "hardware" to realize the algorithms, is undoubtedly a factor having a large effect on the success of CAE.

In addition, the elemental technologies composing the process need to be those which cohere with one another and complement any weaknesses contained therein for realization of highly reliable CAE. The author illustrates the "*Intelligence CAE Software Creation Requirements*" as shown in Figure 7 (illustration: From (i) to (iv)). Though algorithms themselves might be excellent in theory, if they are not properly and efficiently implemented into the calculator, favorable results cannot be expected. As the performance of algorithms largely depends on the compatibility with the modeling, errors in the modeling hinders the efficient performance of the algorithms even though the problem setting is correct.

Compatibility between the algorithms and calculator cannot be overlooked since algorithms which can draw out the best performance from the calculator are able to produce the desired results. In short, when appropriate combinations among the elemental technologies are not selected, the entire process of CAE does not function. In other words, success in CAE depends on the "collective strengths" of the elemental technologies, and this is what we assert here.

Skilled CAE engineers are not experts in all the fields of the elemental technologies, but they understand their characteristics and interactions as “implicit knowledge” and thus conduct selection and combination to obtain favorable interactions and consequently the desired results. The formulation of such “implicit knowledge” confined to the personal know-how of the engineers is an indispensable step to be taken for sophistication of CAE as a problem solving method and therefore it is positioned as a major theme in author’s working.

5. Application Example: *Highly Reliable CAE Numerical Simulation*: Production of CAE Software for Molding Automotive Seat Pads

In this section, the author explains a *Highly Reliable CAE Numerical Simulation* which applies *Advanced TDS*. As an application example, "*Production of CAE Software for Molding Automotive Seat Pads*" is presented here [20]. For the purpose of reducing the trial production period and improving the precision of automotive seat pad molding, a simulation technology was developed for molding urethane foam and it was implemented as a *Urethane Foam Molding Simulator*.

In the development process, particular effort was made to remove the empirical rules and to implement universal equations with a view to responding to original design shapes and complex composition. Consideration was also given to practical use at production sites by enabling simulation in a short period of time. Figure 8 shows the technical element analysis of the *Urethane Foam Molding Simulator* [4].

5. 1 Grasping the Problematic Phenomena

The phenomena associated with urethane foaming in a mold are characterized by its expansion due to its changing composition through chemical reactions and also considerable changes in viscosity. These are the major characteristics of the simulation. These phenomena

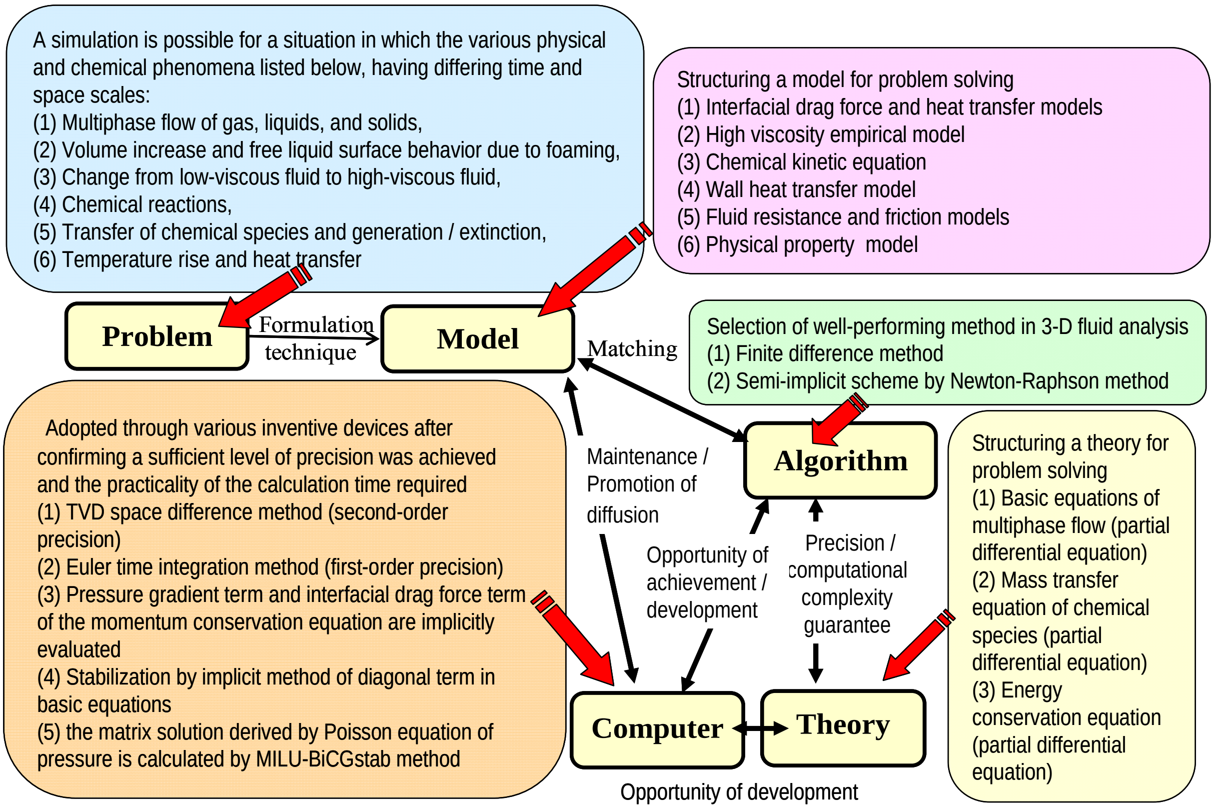

Figure 8 Technical Element Analysis for “*Urethane Foam Modeling Simulator*”

can be roughly divided into: chemical reactions, flow of a mixture of raw materials and urethane foam, transition of the chemical types inside the mixture, the rise in air flow and pressure, and the rise temperature. These in turn can be sorted out as follows:

(1) Multiphase flow of gas, liquid, and solid, (2) volume increase and free liquid surface behavior due to foaming, (3) change from low-viscosity fluid to high-viscosity fluid, (4) rise in temperature caused by chemical reactions and heat generation, as well as heat transfer, and (5) transition of chemical species and generation/extinction.

5. 2 Theoretical Analysis Model

The phenomena roughly grouped in 5.1 can be expressed by chemical and physical equations or analytic models as shown below:

(1) Basic equation of multiphase flow, (2) mass transfer equation of chemical species, (3) biphasic interface model, (4) physical properties calculation model such as the viscosity coefficient (5) chemical kinetic equation, and (6) wall heat transfer and friction model.

The “Basic equation of multiphase flow” or “mass transfer equation of chemical species” above can be expressed by time development-based partial differential equations representing transfer and diffusion of the fluid energy or chemical species concentration. Other items representing the phenomena of heat transfer, wall friction, generation / extinction by chemical reactions, and so on can be added to those equations as needed. Such analytic models as the “biphasic interface model”, “chemical kinetic equation”, and “wall heat transfer and friction model” listed above are additional models, and they can be associated with such time development-based partial differential equations as “basic equation of multiphase flow” or “mass transfer equation of chemical species”.

These additional analytic models are also called constitutive equations, and they are indispensable for completing time development-based partial differential equations. Generally speaking, constitutive equations are used to model phenomena wherein temporal and spatial scales are largely different from the phenomena expressed in partial differential equations.

They are also used in cases where the phenomena are difficult to express in equations or theoretical formulas dealing with physical properties. Many of these are often based on the data obtained through experiments, and the physical properties employed are usually calculated by polynomials or exponentials for such physical values as temperature or pressure.

5.3 Implementation of Intelligence and High Precision

In order to conduct simulation while also linking the basic equations and constitutive equations in 5.2 on a computer, numerical modeling is needed. In the urethane foam molding simulator, the basic equations are digitized by using the finite difference method as a numerical analysis method, and the 3D space inside the mold is segmented by rectangular grids for computer simulation.

Setting as the unknown such physical chemical values as pressure, temperature, gas volume fraction, chemical type concentration, etc., digitized equations are solved to find out the spatial distribution of these physical chemical values along with the progress of time. Sufficient consideration must be given to calculation errors and stability in the numerical solution approach. This was adopted in the urethane foam molding simulator along with various inventive devices after confirming a sufficient level of precision was achieved and the practicality of the calculation time required.

However, substantial calculation precision depends on the selection and structuring of the analytic models for the “interfacial drag force and heat transfer models”, “chemical reaction velocity equation”, and “heat transfer and wall friction model” rather than on the numerical solution method. Due caution is needed for the fluctuations, as well as measurement range and conditions, of the actually measured data when it comes to structuring models for simulation. Especially in the case that a model fitted with polynomials is used beyond the measurement range, a totally wrong solution can be obtained instead of the deviation in calculation precision. One of the important requirements for simulation is a capability to conduct calculation in a virtual condition beyond the reality, and this point was also taken into consideration for the modeling process.

5. 4 Development of the “Urethane Foam Molding Simulator”

For the development of the urethane foam molding simulator, the following factors were taken into consideration in an effort to structure a realistic model: examination of the precision of the actually measured data, examination of models appropriate for the capabilities, development period and cost of the assumed calculator, avoidance of calculation instability stemming from temporal and spatial scales, efficient calculation methods leading to better stability, and examination of the precision compared to the experimental testing results, etc.

6. Conclusion

With a view to achieving “worldwide quality competition – simultaneous achievement of

QCD", the authors have promoted the *Advanced TDS, Total Development Design Model*, which is an advanced form of the core *New JIT* technology, *TDS*.

With a view to establishing a development designing quality assurance system necessary for CAE in the advanced manufacturing industry, attention was given to the indispensable *Highly Reliable CAE Model*. When this model was applied to a concrete target, it was demonstrated that a rational arrangement of partial as well as overall optimality is needed for the required technical elements consisting of: "problem – model- algorithm – theory - computer" to be implemented in the *Highly Reliable CAE Numerical Simulation*.

The guidelines for the "implementation of intelligence and high precision into CAE analytic software" were presented, and their effectiveness was verified though the application example *Highly Reliable CAE Numerical Simulation* for the *Production of CAE Software for Molding Automotive Seat Pads - Urethane Foam Molding Simulator*.

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