Thermal/Acoustic trade-off design for Consumer Electronics in a distributed design environment

Kenichi Seki, Hidekazu Nishimura
Graduate School of System Design and Management, Keio University
4-1-1, Hiyoshi Kouhoku-ku, Yokohama Japan
Kenichi.Seki@a7.keio.jp, h.nishimura@sdm.keio.ac.jp

Kosuke Ishii
Department of Mechanical Engineering, Stanford University,
Stanford, CA 94305-4022, USA

Laurent Balmelli, PhD.
Manager,
Product Lifecycle Management
Solutions,IBM Software Group
balmelli@us.ibm.com

Guest Professor
Graduate School of Design and System
Management, Keio University
balmelli@sdm.keio.ac.jp

Abstract. Today's market demand for smaller, more powerful consumer electronics poses a major challenge to the rapid design of products. In addition, the ability to perform strategic coordination amongst different stakeholders within the enterprise increasingly becomes an important criterion to enable global engineering. We begin the paper with an introduction to a typical design process involving distributed design teams In particular the process allows the thermal-acoustic design of cavities, i.e. air space inside the enclosure, in terms of flow rate and acoustic radiation resistance. Then we proceed with the investigation of an approach leveraging recent modelling technology to support such a process efficiently. The process makes use of the system modelling language (SysML.) as product description support and the Design Structure Matrix as an analytical design tool. We use the model and the DSM as a means to drive numerical simulation and perform trade-off studies .Simulation results show that performing trade-off study in the early system design phase leads to a potentially optimal module layout for the problem studied.

Introduction

Product development for Consumer electronics (CE) increasingly requires distributed design activities due to customized requirements based on local market needs, customer preferences, regional broadcast formats, etc. With intensifying competition in digital products, there is a need for rapid product development process spanning product definition to design and down to manufacturing. Hence new collaboration technologies for design knowledge sharing and management are necessary to address the above issues. There are two major difficulties related to collaboration in such a distributed environment:

First, the concurrent execution of collaborative design activities related to sub-system are difficult to optimize due to the lack of knowledge about the effective process dependencies. In other words, some of these dependencies might emerge during the design activities and require a reorganization of the collaborative workflow.

Second, the distributed nature of the design activities and the lack of system-level control over the key performance measures (KPI) for the entire system often lead to sub-optimal design characteristics, as well as poor design cost and time performance.

In this work we address a particular instantiation of the process described above, namely the joint design of acoustic and thermal features in a consumer electronic product. This process is well established in the industry and manufacturers resort to simulations and best-practices to tackle design issues. Moreover mechanical product simulations are an active area of research. Unfortunately, issues attached to the design process often prevent designers to perform trade-off studies over the entire product. As a result they permit a systematic approach to optimization. In contrast, we show with this study that a systems engineering approach to this problem allows multi-domain optimization, as well as a framework to perform trade-off studies across the entire design.

Our approach to optimize the execution of the joint acoustic/thermal design process explained in the previous section by combining the Design Structure Matrix with a system-level modeling approach. The system model is expressed using the Systems Modeling Language (SysML). We briefly introduce these two methods below.

The Design Structure Matrix (DSM) is an analytical representation that allows the representation of structural dependencies using a matrix representation. Multiple representations for the DSM have been developed and are thoroughly documented in the literature. In this work, we are using a DSM representation to quality data dependencies between tasks in the processes described in Section 2. More precisely, we use the so-called task-based DSM and use it to determine an optimized execution sequence of process tasks. The optimized sequence of execution maximizes the concurrency of execution across process tasks, i.e. it minimizes the number of steps to complete the execution.

We represent the architecture of the product developed throughout the thermal/acoustic process using a system-level approach, i.e. we make use of formal representation of the product under development using the SysML language. In particular, we represent systems of different nature, namely electronics and mechanical in a single representation in order to represent analytical dependencies between them. These dependencies translate into design issues and constrain the execution of the attached processes. This approach is known as system-level modeling and aims at the improvement of inter-disciplinary collaboration. A overview of this approach is available in (Balmelli, Purpose of Systems Modeling).

Technical Background

Thermal Design Process

In this section we describe a typical approach to a thermal design process and review a set of trade off studies performed during the system design phase. The design process can be divided into four concurrent groups of activities: (1) Product Definition, (2) ASIC Design (below System in Package, or SiP design) (3) Circuit Board Design (below PWB design) and (4) Product Design. These four groups are each composed of a 10 to 15 tasks. Tasks are dependent among each other though their inputs and outputs, both within and between groups of activities.

The amount of dependencies between the design tasks requires engineers to perform a series of iterations. In order to maximize the amount of concurrency, hence reducing the number of iterations, two approaches are currently under investigation: (1) Initial Target Values (ITV) and (2) Design Target Transfer (DDT).

ITV allows designers to start tasks early by setting input parameter to their own design. ITV's play the role of tentative values for thermal boundary condition applied to each system. These values are derived from knowledge databases built from past product development experience. Note that this technique is still at its infancy and is being progressively adopted across the industry.

DTT is essentially a means to create ITV's: Engineers communicate expected design parameters to dependent design team based on prediction method. Both ITV's and DTT allow the reduction of iterations and improve overall process KPI. In contrast with ITV, DTT is not widely applied throughout the industry due to the difficult of scheduling development activities, sharing resources and identifying design dependencies.

The amount of concurrency necessary to perform the thermal design is actually clearly visualized using the task-based DSM show in Figure 1. In the matrix, row and columns represent design tasks in a symmetric fashion. A crosshair in a cell represents input data dependency. Both ITV and DTT are adequately presented using the DSM. For example, the matrix is read as follows: the task n in column n inputs data to the task m in row m. For example, task 1 (Set user target) provides data to tasks 2, 3, 4 (in the group Product Definition), 35, 37, 38 (PWB Design), and 47 (Product Design).

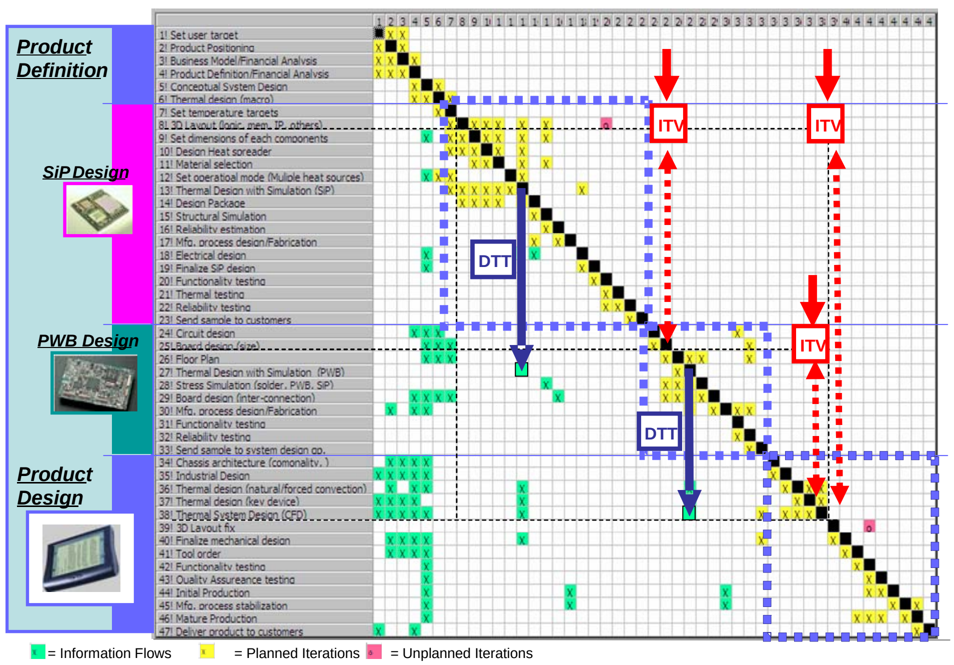

Figure 1. DSM of Consumer Electronics thermal design

Therefore, following the example above, all the crosshairs below the matrix diagonal are forward dependencies, i.e. the tasks enumerated above must wait for Task 1 to finish. Therefore to allow for earlier start, Task 1 could provide an early estimate for its output (i.e. through DTT) to its dependents. Similarly, crosshairs above the diagonal are feedback dependencies. For example, Task 1 must receive input from Task 2 and 3 in order to start. Since Task 2 and 3 also dependent on an input from Task 1, these tasks are inter-dependent and performed in parallel. In the case of feedback dependencies, ITV's are provided for tasks to allow earlier start.

Eventually, since ITV's and value obtained through DTV are estimates, inter-dependent tasks need iterations to converge to the final design characteristics.

The above process suffers from several drawbacks: First, recall that this process is executed across distributed design team (Section 1), which renders the efficient sharing of data quite difficult. Moreover, unknown design hurdles, such as unplanned iterations complicate the sequencing of tasks. For example, in the thermal design process, unplanned iterations arise from the difficulty to estimate thermal boundary conditions for systems (2008 Seki et al.) In particular, usable estimates are usually known through the creation of physical prototypes. Finally, as mentioned in Section 1, the iterative, distributed nature of task makes for a difficult, almost impossible tracking of global product metrics.

Acoustic Design Process

This section describes a typical range of acoustic design issues for reducing noise caused by products. Noise reduction frequently causes a problem at a later step of system design (see the design task analysis shown in Figure 2). Figure 2 shows the design process made by the Design Structure Matrix (DSM) analysis according to the actual model design history. In this example, further noise reduction is required in a process of system performance verification. Therefore, damping materials and porous absorbers are added or changed, but the expected silence characteristic cannot be acquired at this step. To get the expected noise reduction, the design process is returned to the step of the thermal design (which includes the fan unit selection and component layout change in the cabinet), and then major design change is made.

As described in the previous section, since products are becoming more compact, the integration between physical modules becomes increasingly difficult. In particular, it is difficult to simultaneously satisfy multiple characteristics such as mechanical and electric characteristics. This satisfaction includes the above-mentioned solution of both heat and noise reduction problems. In the next section, we will further examine why harmonization of thermal design with noise design is difficult in mass-production design.

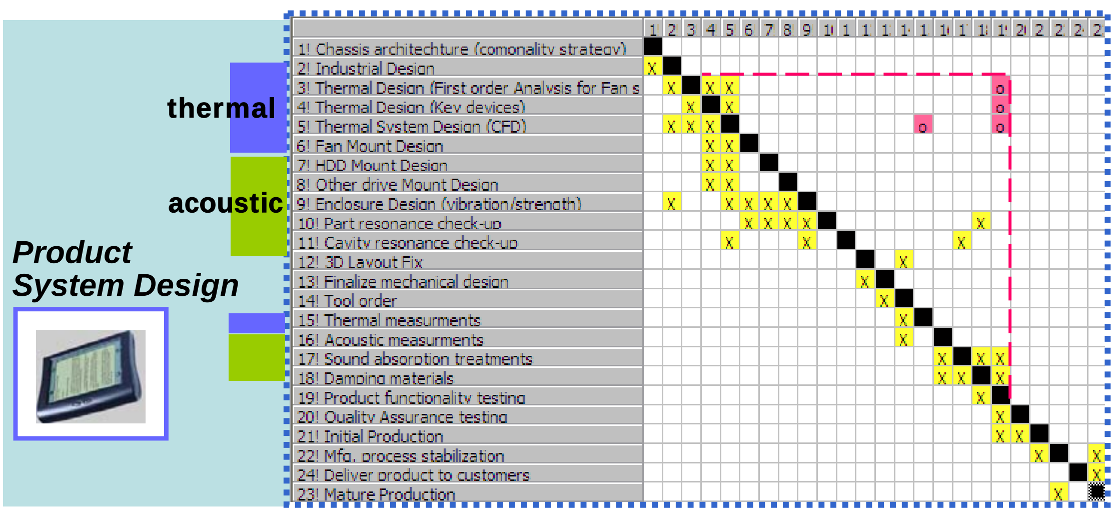

Figure 2. DSM of Consumer Electronics thermal/acoustic design

Joint Thermal-Acoustic Design Process

This section describes the details of the cabinet system design viewed from the thermal design and noise design standpoints. A real device produced after prototype evaluation is used to examine the device performance. Figure 3 shows an example of measurement settings for structural design verification by using flow rate and pressure measurement results. A check is made to see whether the earlier prototype has a flow rate required in the thermal design. As already explained in the design task of the DSM analysis, we must start the design of component layout, cabinet structure, and vents according to the system thermal design plan. The minimum flow rate for heat dissipation must be acquired by combining the used fan unit with the cabinet airflow resistance. This resistance depends on the structure of the vent grills and cavity space in the cabinet. The evaluation experiment shown in this figure is performed to check the pressure and flow rate characteristics of the prototype.

Figure 4 shows the experiment settings of the same prototype for evaluating the acoustic performance caused by the product. The most important structural condition that affects the acoustic radiation power is the acoustic radiation efficiency of the product system. The acoustic radiation efficiency depends on the cavities and ventilation opening of the cabinet, in the same way as the above flow-rate characteristics.

Structural strength and vibration characteristic mainly depend on the module structure itself to be designed. On the other hand, cavities in a cabinet are examined and designed by many module designers, but special designers in charge of space design are rarely prepared. In addition, the flow rate and thermal condition depend on the pressure control in the cabinet space, and the acoustic radiation efficiency depends on the cavity space dimensions and boundary conditions. Thus cavity conditions determine many other characteristics. It can be considered that this makes the thermal and noise condition balance difficult in the device system design of the same type.

As described before, the DSM analysis sometimes requests design process returning to a previous step, and the cavity characteristic largely affects other characteristics. This case shows that the design of the cavity space is very important in all the design phases.

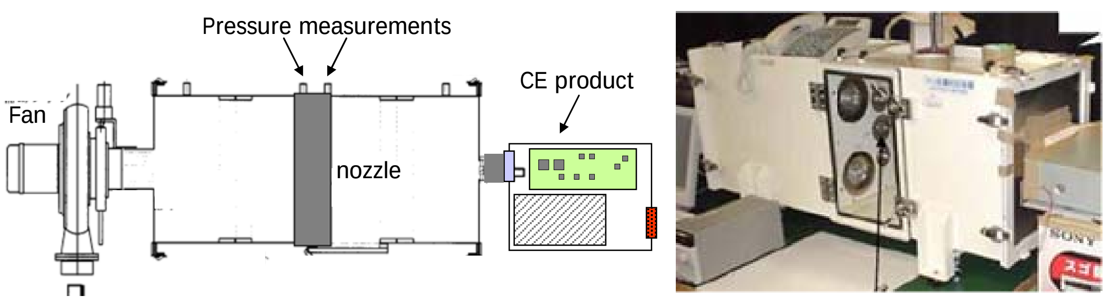

Figure 3. Flow characteristics verification

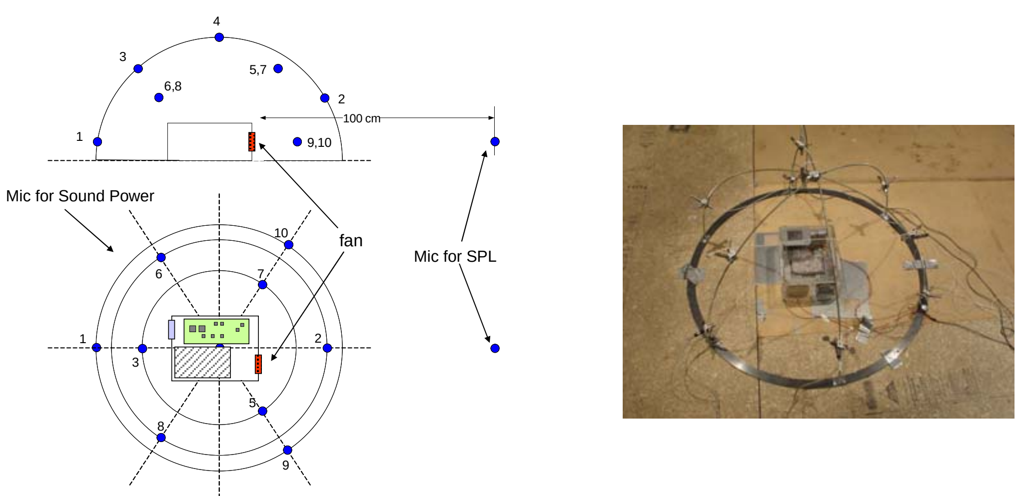

Figure 4. Acoustic characteristics verification

Design Trade-off Problem

The previous section described the importance of cavities of which characteristics were determined mainly in the layout design, and described that the appropriate characteristic management in the work division system was difficult. On the other hand, this section describes the heat dissipation and noise reduction problems of a concrete stationary AV device. The tradeoff problem between the heat dissipation and noise reduction must be resolved in the design process by clarifying the performance design targets and restriction conditions and by considering the DSM analysis described in the previous section. Needless to say, necessary functional conditions must be satisfied in the design of the product having multiple functions. In this section, we will examine the design approach for determining the optimal balance of the total system.

When an attempt is made to optimize the above system design in the organization in which respective modules are to be designed by different design teams, the same product model should be shared by all the design teams in all the processes from planning to mass production. However, different models are actually used depending on the purposes and designers in requirement analysis, software design, electric design, mechanical design, parts list creation, etc. This complexity is the main cause of difficult resolution of the above design tradeoff problem. The final target of this study is to advance product development on the model basis. The design tradeoff problem is described in SysML, which is used in model-base system design. In Figure 6, we show the actual structure of the Audio-Video system. Figure 7 shows an analytical view if the same system, and points out the equations governing the thermal equilibrium of the system. In particular, Usys and Tsys govern the overall balance of the system. The output Qout depends on the choice of fan (e.g. performance and the impedance of the system. We express the current parametric relationships though the use of the SysML parametric diagram shown in Figure 9. Figure 8 shows the energy input/output between the fan unit and system when viewed from the acoustic design standpoint. The fan unit operates as a flow-rate generation device in thermal design, but operates as a noise source or a vibration source in acoustic design.

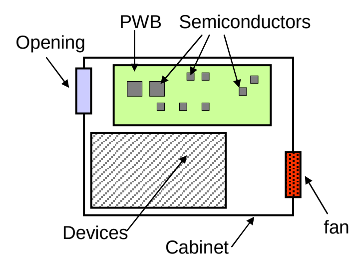

Figure 5. AV system

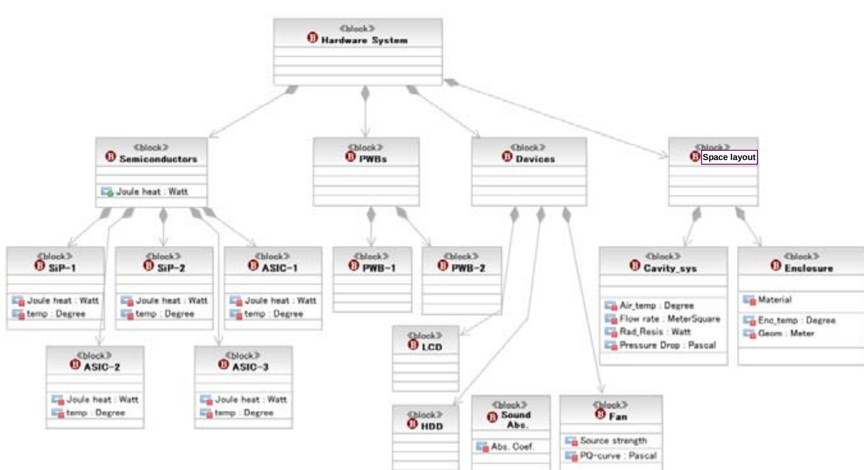

Figure 6. Hardware Structure

In the acoustic design of the system, the most important factor is to design the internal space and opening section of the cabinet in order to minimize the efficiency of the acoustic radiation to the outside of the system. Equation (1) shows the fan characteristic II of an acoustic source of the dipole type. The acoustic radiation efficiency is determined from the combination of the fan characteristic with the acoustic space in the cabinet. The internal space of the cabinet must be designed from the acoustic viewpoint according to the acoustic radiation efficiency as a restriction condition. The product has acoustic characteristic restrictions as well as thermal characteristic restrictions. Figure 9 shows these acoustic characteristic restrictions.

$$\Pi = \frac{\rho\omega^4}{12\pi c^3} D^2 = \frac{\rho\omega^4}{12\pi c^3} d^2 Q_{acoustic}^2 = R_d \cdot Q_{acoustic}^2 \tag{1}$$

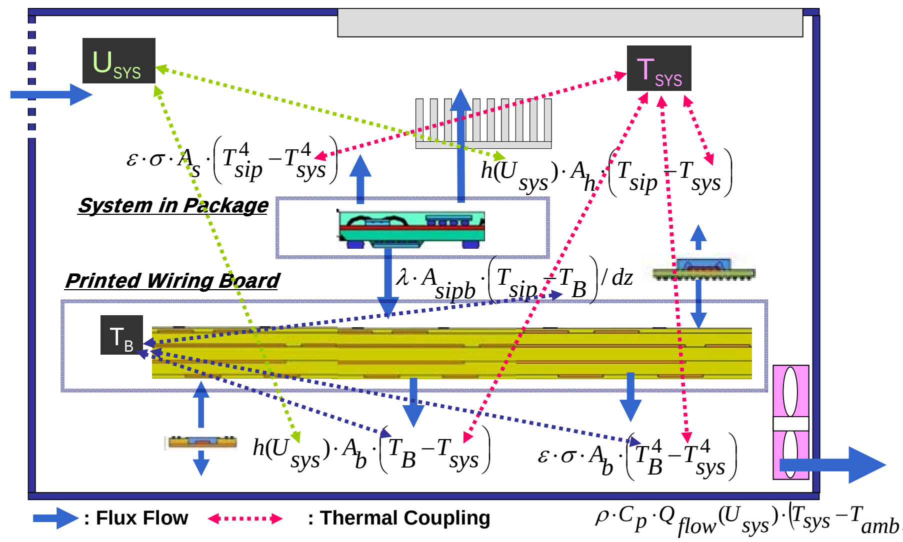

Figure 7. Thermal energy flow

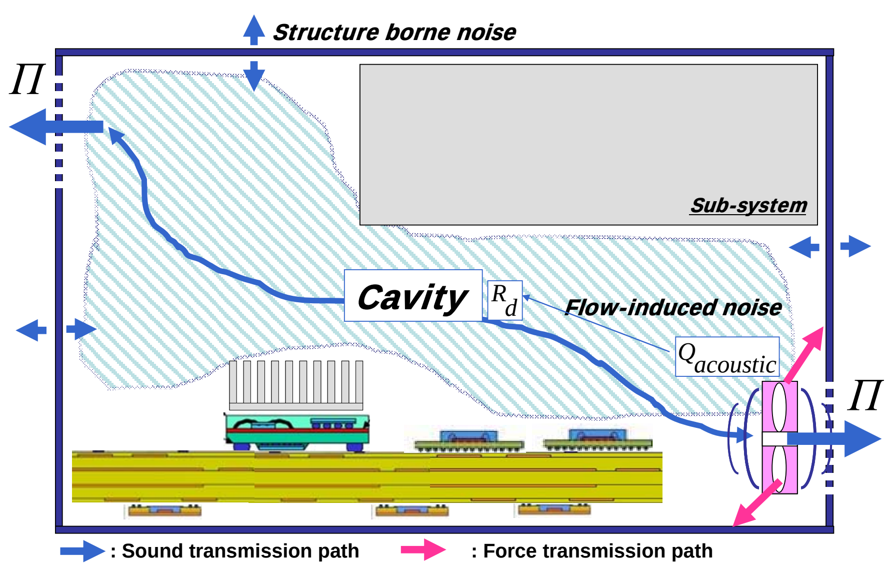

Figure 8. Acoustic energy flow

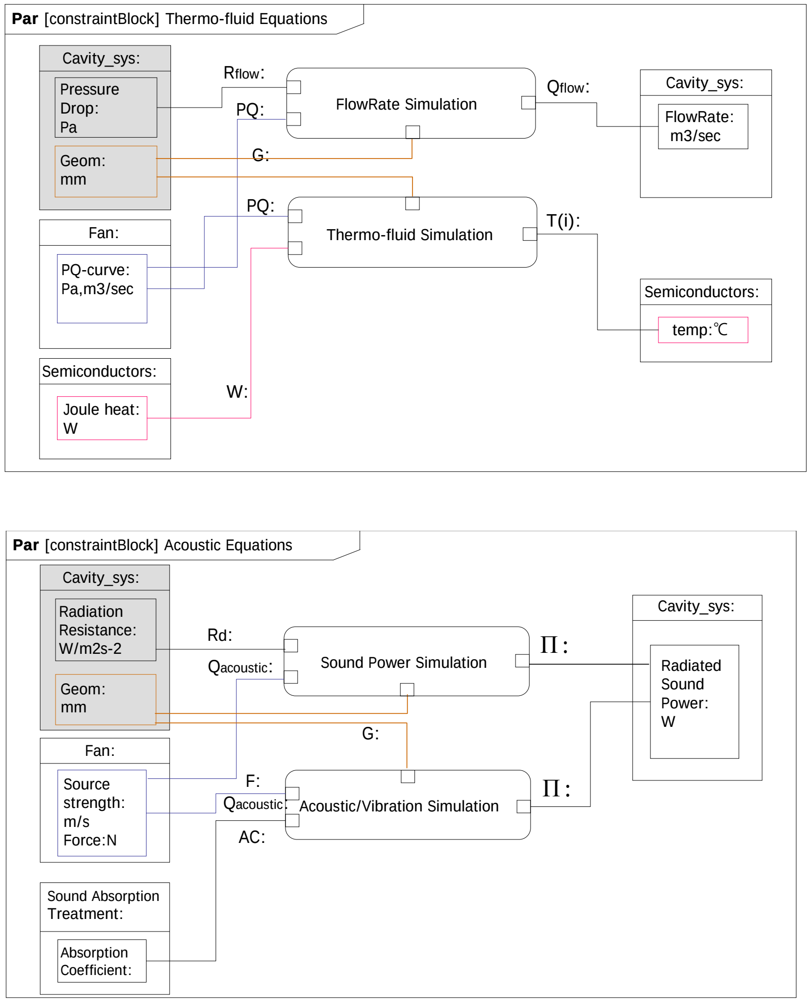

Figure 9. Thermal / Acoustic Design Constraints

Table 1 lists thermal-acoustic design tradeoff problems viewed from the point of design parameters for balanced multi-functions for the thermal radiation and noise reduction design shown in Figure 2. The performance design targets, restriction conditions, and multiple performance are well balanced based on the above basic design concepts.

Table 1. Thermal/Acoustic trade-off design problem

	Thermal	Acoustic
Behaviors	Forced convection cooling (Eq.1)	Sound Radiation (Flow induced and vibration)
Design Constraints	Flow rate → LSI's temperaure	Radiated Sound Power
Design Parameters	Cavity geometry (modules 3D layout in enclosure), Fans' selection/layout, openings' number/position	

Simulation results

A successive design flow must be verified to improve the thermal and acoustic performance by using the preliminary performance verification process using numeric simulation for the design tradeoff problem listed in Table 1 in the previous section. The following describes a case of the tradeoff design using a numeric model applied to the consumer product shown in Figure 5.

Figure 10 shows the 3D geometric model, thermofluid simulation model, and acoustic radiation characteristic analysis model of a stationary AV device. The thermofluid model is an orthogonal difference-lattice calculation model for which the main-component thermal transfer and cavity and surrounding airflow in the cabinet can be counted by coupled calculation. The acoustic model is a boundary-element-method calculation model for which acoustic radiation inside and outside the device can be calculated simultaneously.

The above two simulation models use the same geometry information on the cavities that are most important design components in this tradeoff design. About the axial fan unit, the thermo-acoustic model is created according to the actually measured fan PQ characteristic, and the acoustic model is created by handling the fan unit as a dipole acoustic source. The acoustic source energy as a unit acoustic source is used for comparison operation for design check.

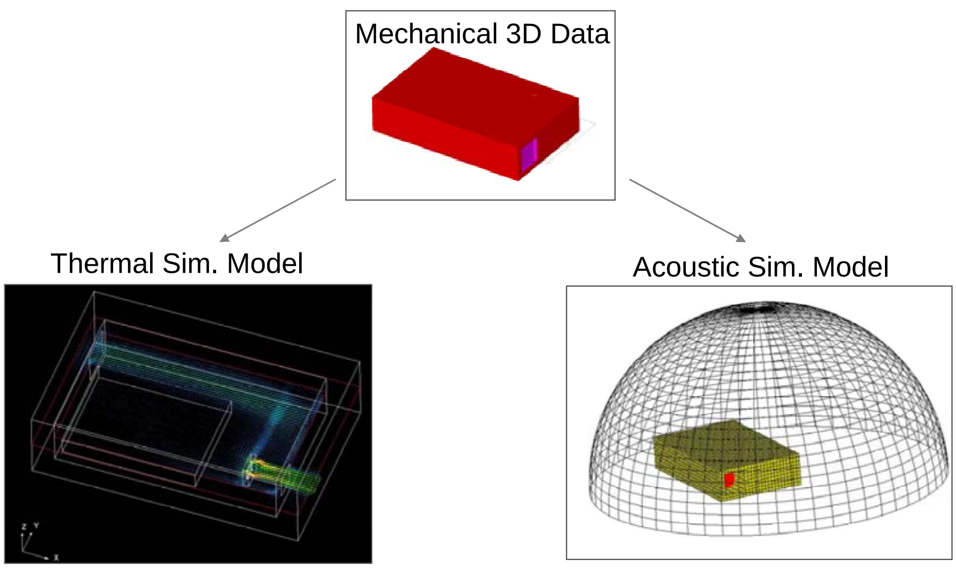

Figure 10. Thermal and Acoustic Analysis model

As shown in the DSM analysis results in Figure 2, the major component layout in the system design is initially determined according to the thermal design concept by generally considering the electronic-circuit basic operation and element reliability. In this case, considering the macro thermal balance of the product, general engineers employ the air ventilation structure in which a forced circulation fan unit is mounted on a ventilation orifice made on a cabinet. Forced circulation fan units are generally considered to have high fan ventilation efficiency. After this major component layout phase, detail design of the internal structure is advanced from the viewpoint of thermal and vibration acoustic characteristics. Then in the final phase, the necessary performance of the system is confirmed through a real-device test. If the necessary performance is not acquired in this phase, local measures are frequently added, for example, radiators such as heat sinks are added for thermal characteristic improvement, and noise absorbing materials or noise attenuation sheets are added for acoustic characteristic improvement.

As described above, basic thermal and acoustic characteristics are determined using the cavity structure and depend on the main device layout (e.g., fan unit layout) and cabinet structure. However, the basic layout is usually determined by considering a single performance as stated previously. There are not many cases where the basic layout is examined in the earlier stage of system design by considering the tradeoff of multiple characteristics. For example, the basic layout of multiple fan units largely influences the total acoustic radiation efficiency of the product. Therefore, this basic layout should be determined in the earlier stage of the thermal design by considering also the impact on the acoustic characteristics. This may make unnecessary the product development process returning from a later step to an earlier step, may reduce the number of necessary local components to be added for improvement, and may provide merits in both development period and cost.

This study shows a simple case of tradeoff design. In this example, good structure can be formed in an earlier step of system design by evaluating the impact of fan-unit layout change on both thermal and acoustic characteristics on the numeric-value model base.

Figure 11 shows an example of the calculation results. A general layout, in which an intake vent and a fan unit are placed at both ends of the cabinet, is shown at the left side of this figure. When the fan unit position is changed as shown at the center and right side of the figure, the expected characteristics vary.

The lower part of Figure 11 shows the results of acoustic radiation analysis. The acoustic pressure distribution in the cavity is made by the airflow sound component depending on the fan rotational frequency. As the sound waveform in this frequency band is considerably larger than the cavity dimension, the acoustic source should be placed at the inner side of the open end as far as possible in order to suppress acoustic radiation as a physical phenomenon. Next, when the secondary and tertiary constituents of BPF are considered and when there are multiple fan acoustic sources, more detail examination should be made by considering the mutual action with the internal air-column resonance pattern in the cabinet. In many cases, there is tradeoff relationship between the fan unit layout (in the acoustic design) and the fan unit layout (in the thermal design for ventilation efficiency improvement in the cabinet). In actual design of mass-production products, the thermal design is usually performed before the acoustic design, and the basic design is usually performed before taking the local measures.

Figure 12 shows the design tradeoff results in the case of layout change of one fan unit. For simplification, two indexes are considered: (1) ventilation flow rate in thermal design and (2) external acoustic radiation power at a target frequency in acoustic design. The vertical axis of this figure shows an outlet flow per minute, and the horizontal axis shows a margin of the target acoustic radiation amount. As shown in this figure, even if the target acoustic characteristic is not acquired in configuration that is used in ordinary initial design, significant acoustic improvement by fan layout change can be expected in an allowable range of flow-rate reduction. This acoustic improvement is shown in the margin area at the right side of this figure. By the same approach as this study, simulation of the same type can be explored for multiple layout plans usable in the module layout. For the tradeoff design of the above two evaluation indexes, this simulation can provide the design parameters optimal for the total system.

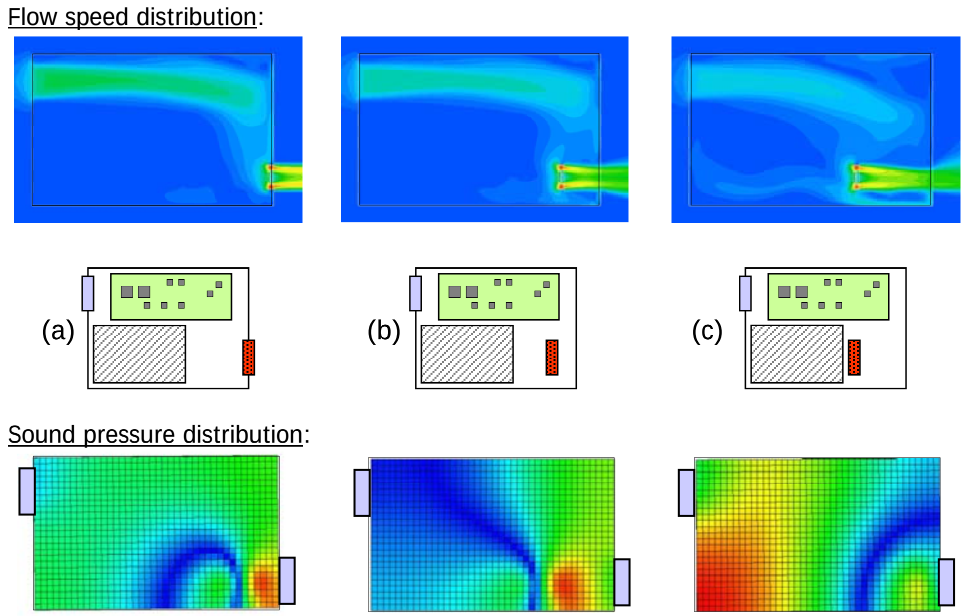

Figure 11. Results of simulation based trade-off study

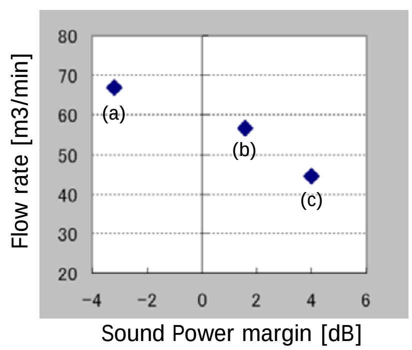

Figure 12. Trade-off Results (Objective Space)

Conclusions

In this paper, we presented a system-level modelling approach to undertake the joint optimization of thermal and acoustic design. In particular, the approach encompasses the analysis of customer requirements, the verification of the product architecture, and the design of modules and sub-systems.

As a concrete example, we introduced the design of an audio-video system. We use the DSM to analyse data dependencies between tasks. Using the DSM, we were able to identify design constraints between design silos. In particular the use of SysML allowed us to express simulation parameters and perform joint optimization across thermal and acoustic disciplines.

In particular, we showed that the joint optimization allows trade-off between a set of competing parameters to eventually lead to an optimized solution. The optimized solution satisfied system-level constraints (as opposed to discipline-specific) hence potentially leads to superior solutions as compared to the state of the art.

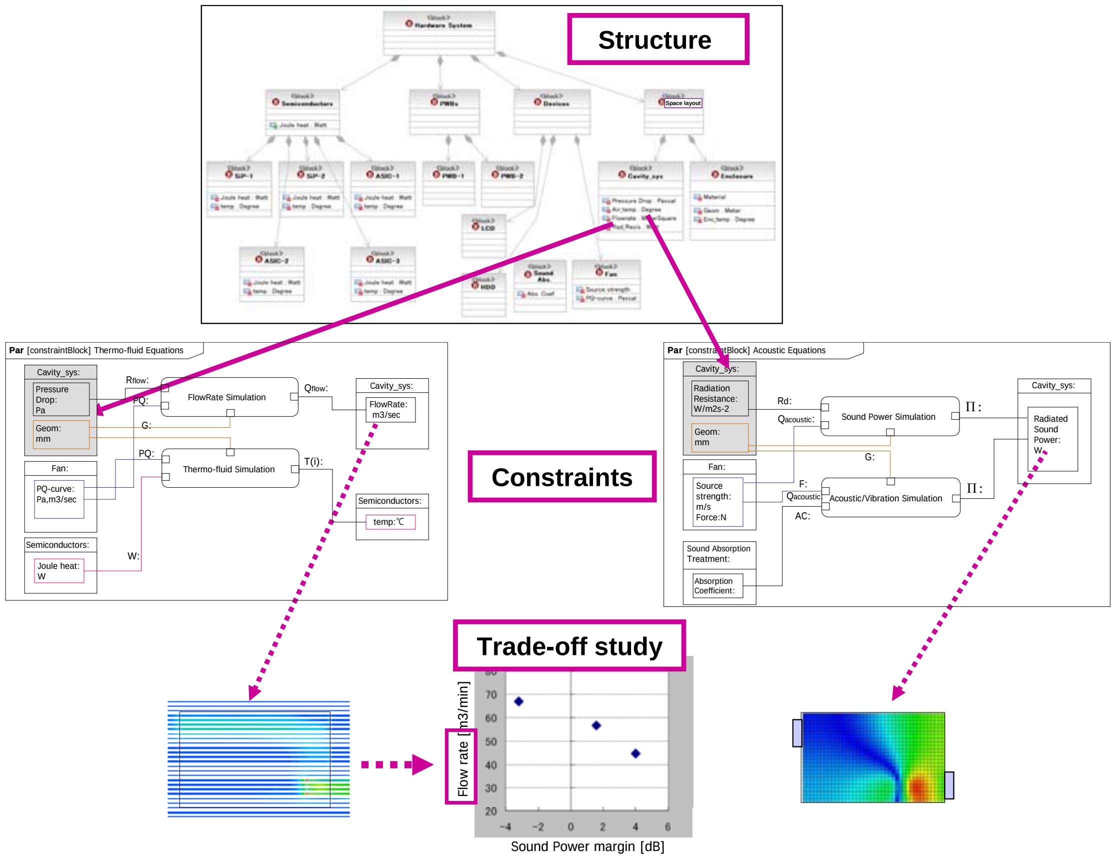

Figure 13. Thermal/Acoustic trade-off design concept

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Biography

Kenichi Seki is now a PhD student of Graduate School of System Design and Management, Keio University under the supervision of Prof. Nishimura. His research area includes design methodology development for thermal and acoustic problems of consumer products. He is a member of INCOSE and JSME.

Hidekazu Nishimura is now a professor of Graduate School of System Design and Management, Keio University, Japan. His research area includes mechanical systems control and motion control for dynamical systems. He is now interested in model-driven systems engineering and systems design of products. He is a member of INCOSE, IEEE, JSME and JSAE.

Kosuke Ishii is a professor of Department of Mechanical Engineering, Stanford University. His research develops methods and tools to improve the life-cycle quality of products. He applies optimization and other modeling techniques to support design and manufacturing decisions in product development. He is a member of Science Council of Japan, ASME Fellow, Visiting Professor at Keio University, and Toyota Production Engineering Advisory Professor.

Laurent Balmelli is currently a manager at IBM in charge of architecting the new generation of offerings and tools for Systems Engineering and Product Development Since 2003, He has represented IBM within the SysML standard team and is one of the lead authors of the SysML language specification. He is invited professor at Keio University in Tokyo Japan.